A Search for Supersymmetry Using Events with Photons and Large Missing Transverse Energy at CMS

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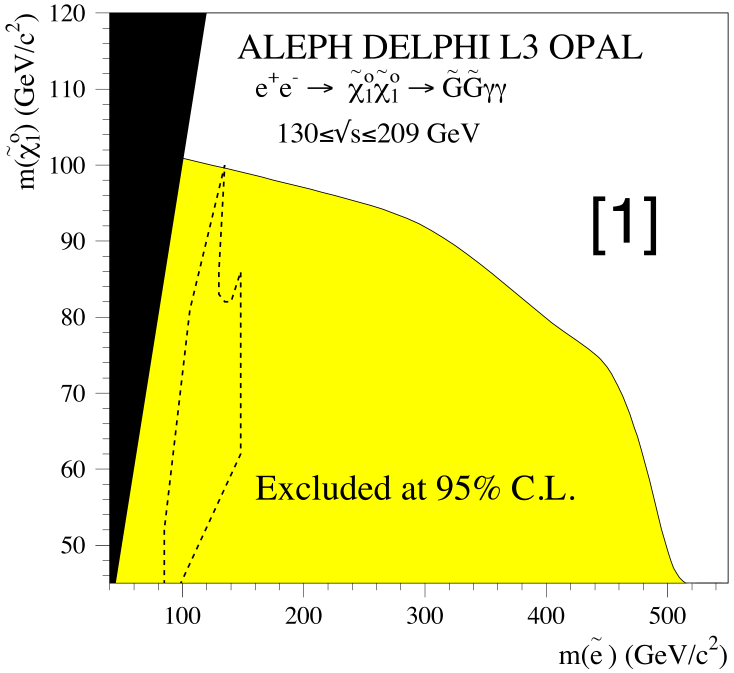
on behalf of the CMS collaboration

Outline

- Introduction
  - Gauge-mediated SUSY searches with photons
  - Next-to-lightest superpartner (NLSP) type → final state
  - 3 complementary searches
- Physics object selection in CMS
  - Photons
  - Jets and missing transverse energy (ME_T)
  - Leptons
- Event selection
- Backgrounds
- Results
- Interpretation in terms of simplified SUSY models
- Conclusions

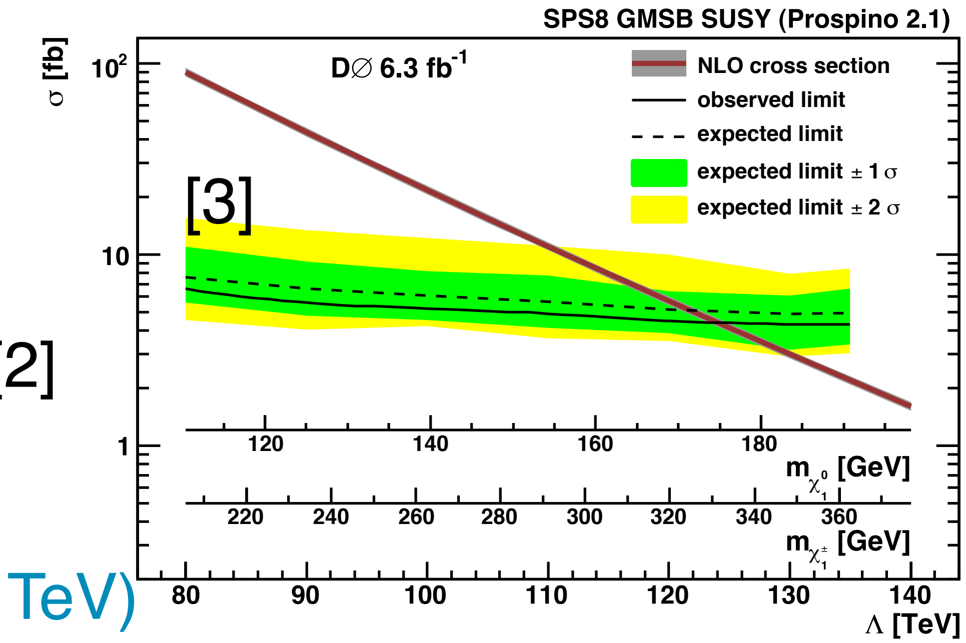
CMS-PAS-SUS-11-009
arXiv:1105.3152

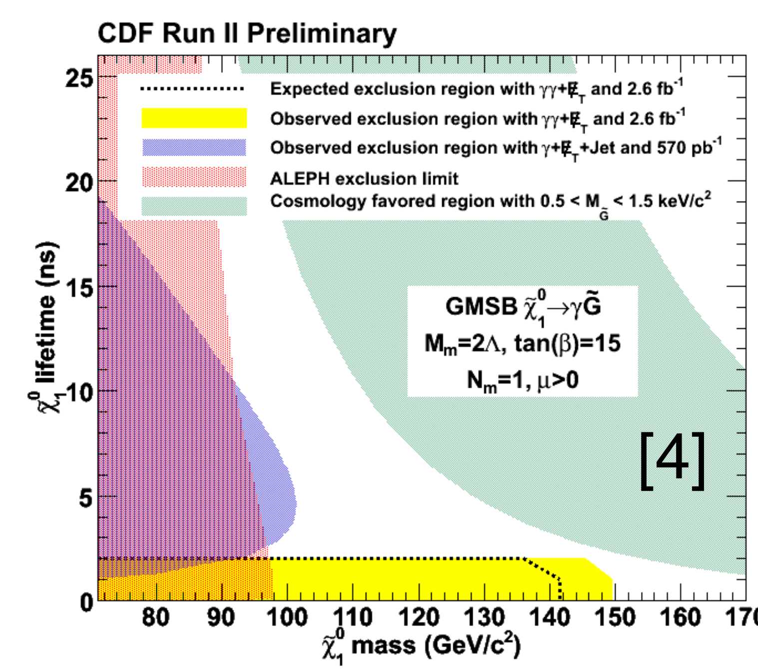
Gauge-mediated SUSY searches with photons



LEP (1989-2000)
- Minimal GMSB model (SPS8) [2]
- Neutralino pair production
- $m_{neutralino}$ > 97 GeV for short-lived neutralino

Tevatron Run II (2001-2010)
- Minimal GMSB model (SPS8) [2]
- Chargino and neutralino pair production
- $m_{neutralino}$ > ~170 GeV (Λ > 124 TeV) for short-lived neutralino

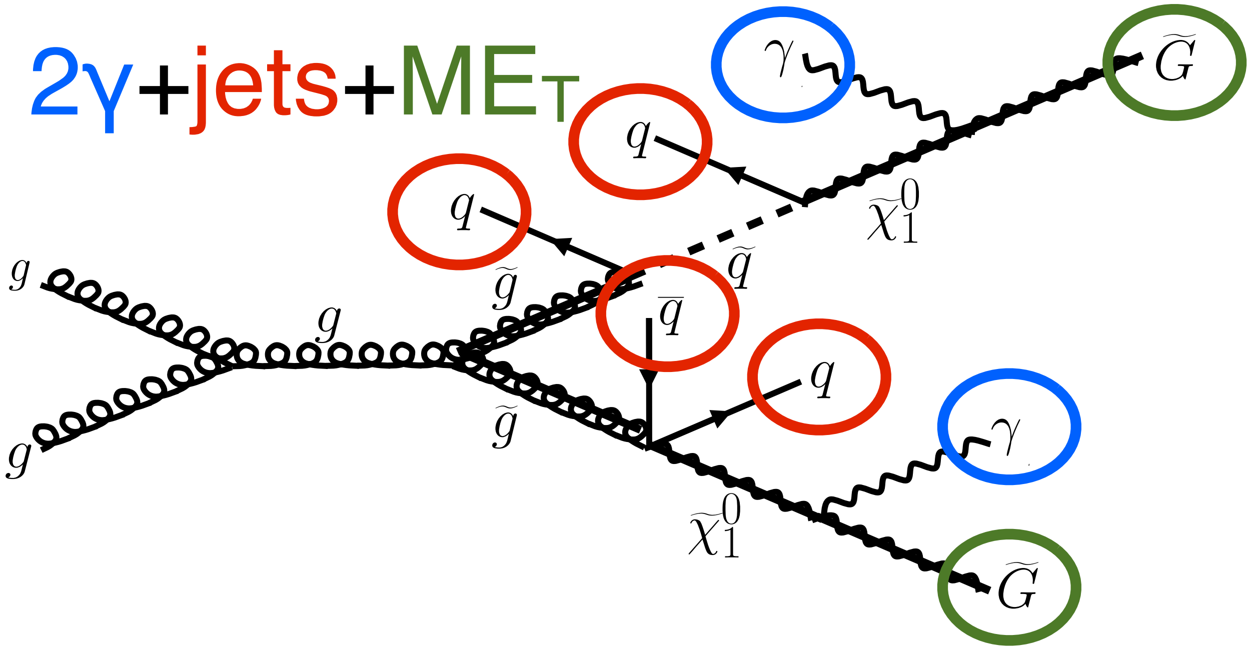




LHC7 (2009-2011)
- General model parametrized in terms of tan β and squark, gluino, and wino/bino/higgsino masses
- No assumptions on the number of messengers, the messenger mass, or the SUSY breaking scale
- Squark and gluino production
- Short-lived neutralino

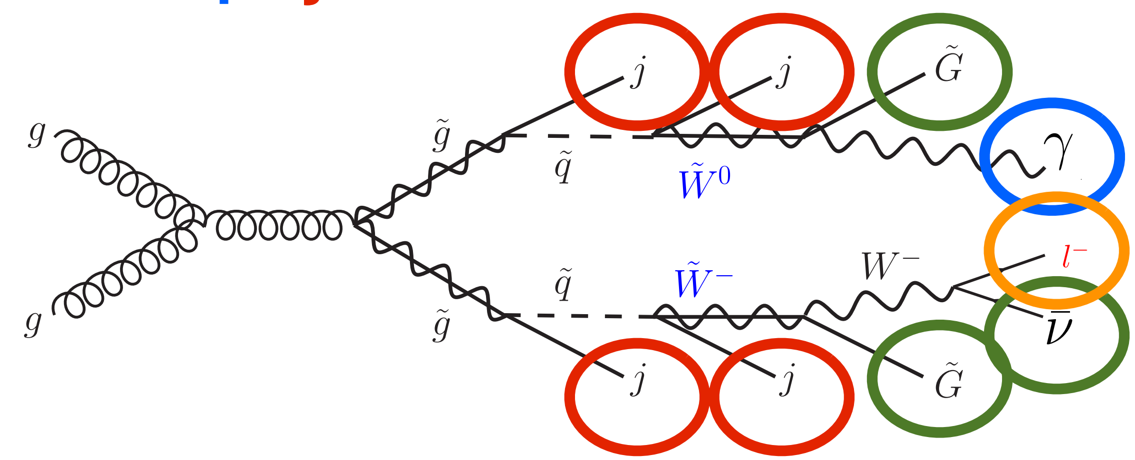
GGM final states

2γ+jets+MET



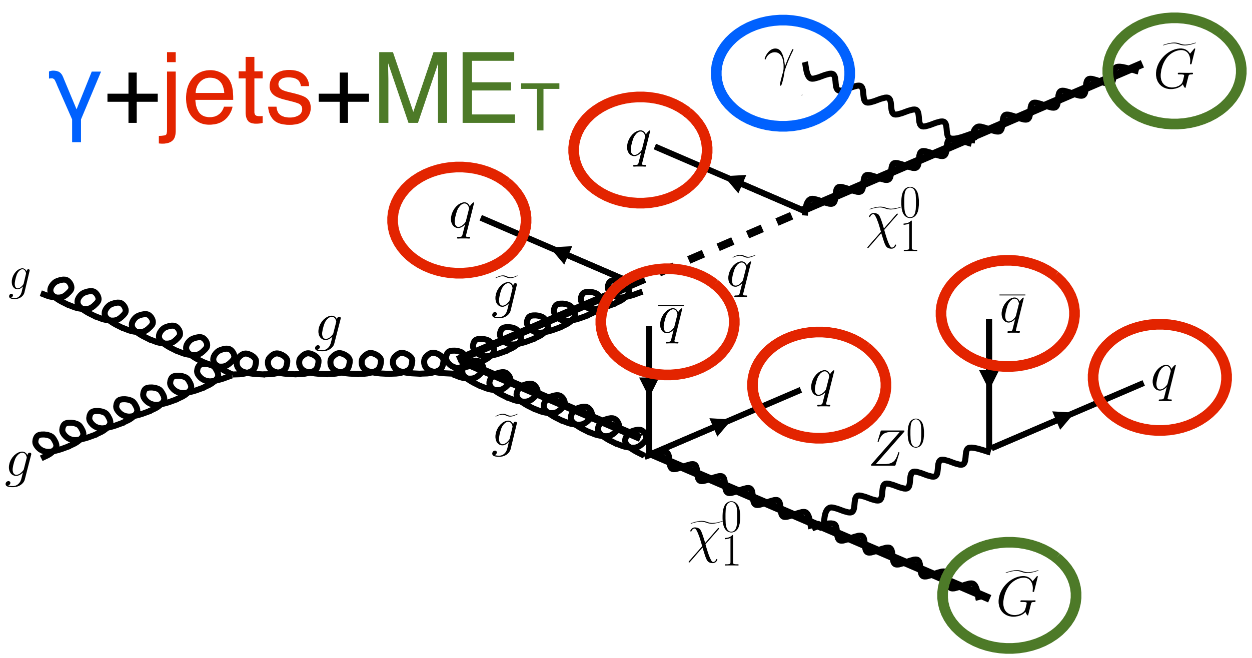
Bino NLSP: neutralino(bino)→**γ+gravitino**

l+γ+jets+MET



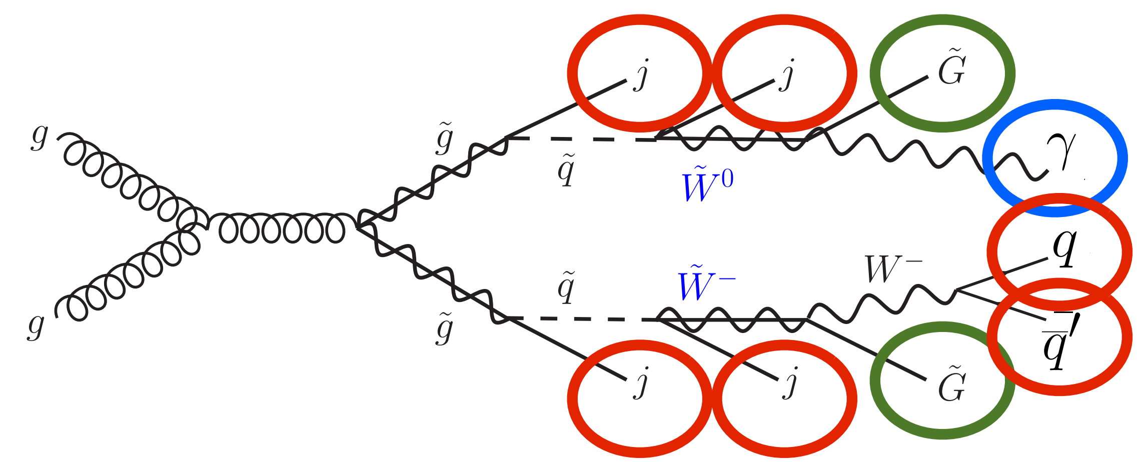
Wino NLSP: neutralino(wino)→**γ+gravitino and** chargino(wino)→**W(→lν)+gravitino**

γ+jets+MET



Bino NLSP: neutralino(bino)→**γ+gravitino or** neutralino(bino)→**Z(→jets)+gravitino**

γ+jets+MET



Wino NLSP: neutralino(wino)→**γ+gravitino and** chargino(wino)→**W(→jets)+gravitino**

3 complementary searches

Search #1: **2 photons + ≥1 jet + ME_T (bino NLSP)**

1.14 fb^{-1}

Search #2: **photon + lepton + ME_T (wino NLSP with leptonic W decays)**

36 pb^{-1}

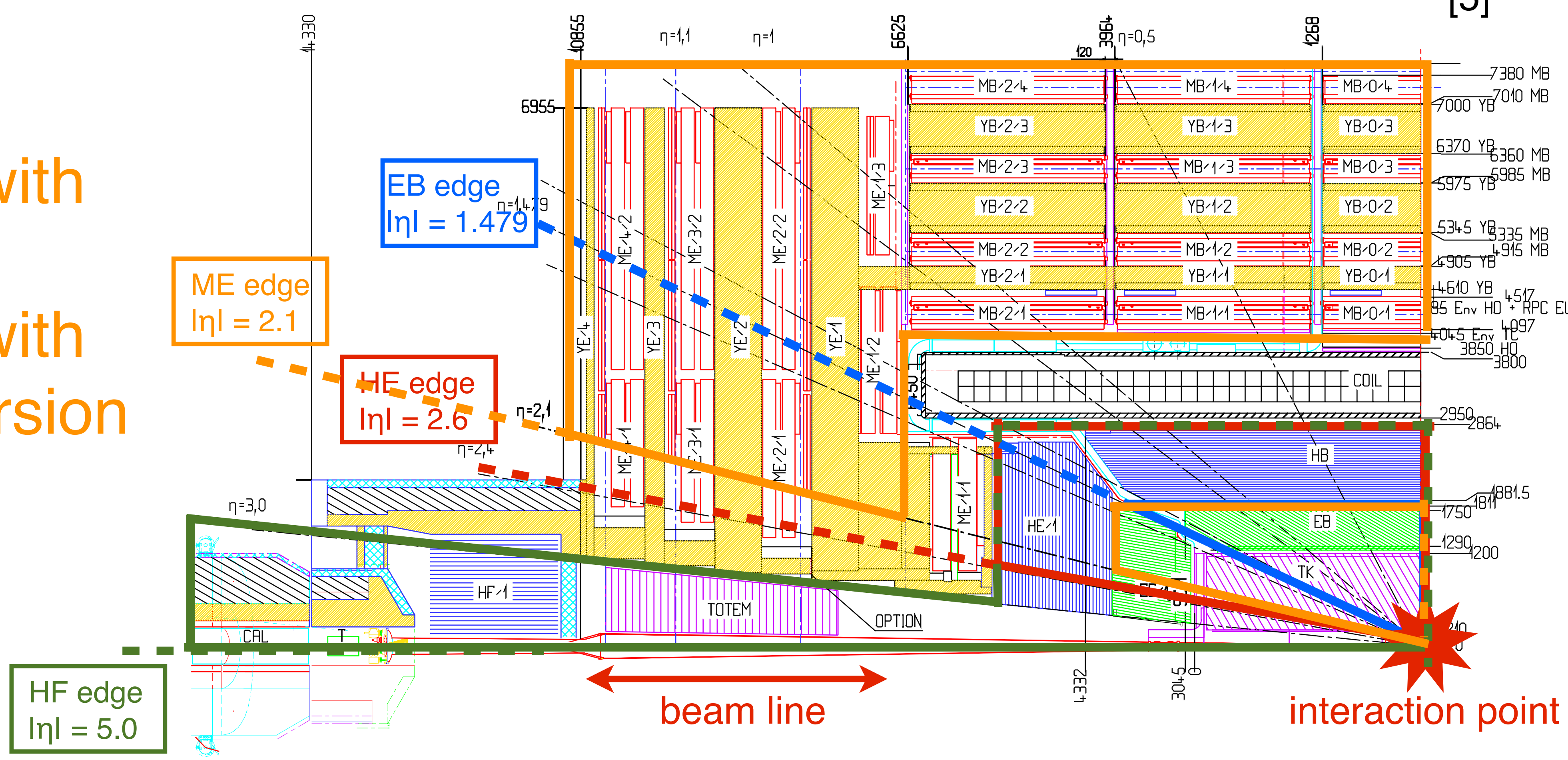
Search #3: **photon + ≥3 jets + ME_T (bino NLSP, wino NLSP)**

1.14 fb^{-1}

Physics object selection in CMS

- Isolated leptons
  - Electrons
    - Inconsistent with ECAL noise
    - Inconsistent with photon conversion
  - Muons

[5]



- Isolated photons
  - Inconsistent with ECAL noise
  - **No matching hit pattern in the silicon pixel detector**

- Jets and ME_T
  - Anti-k_T algorithm with R = 0.5
  - Inconsistent with ECAL and HCAL noise

Event selection

- Using the CMS reconstructed physics objects, build 3 different event selections corresponding to the 3 GGM topologies

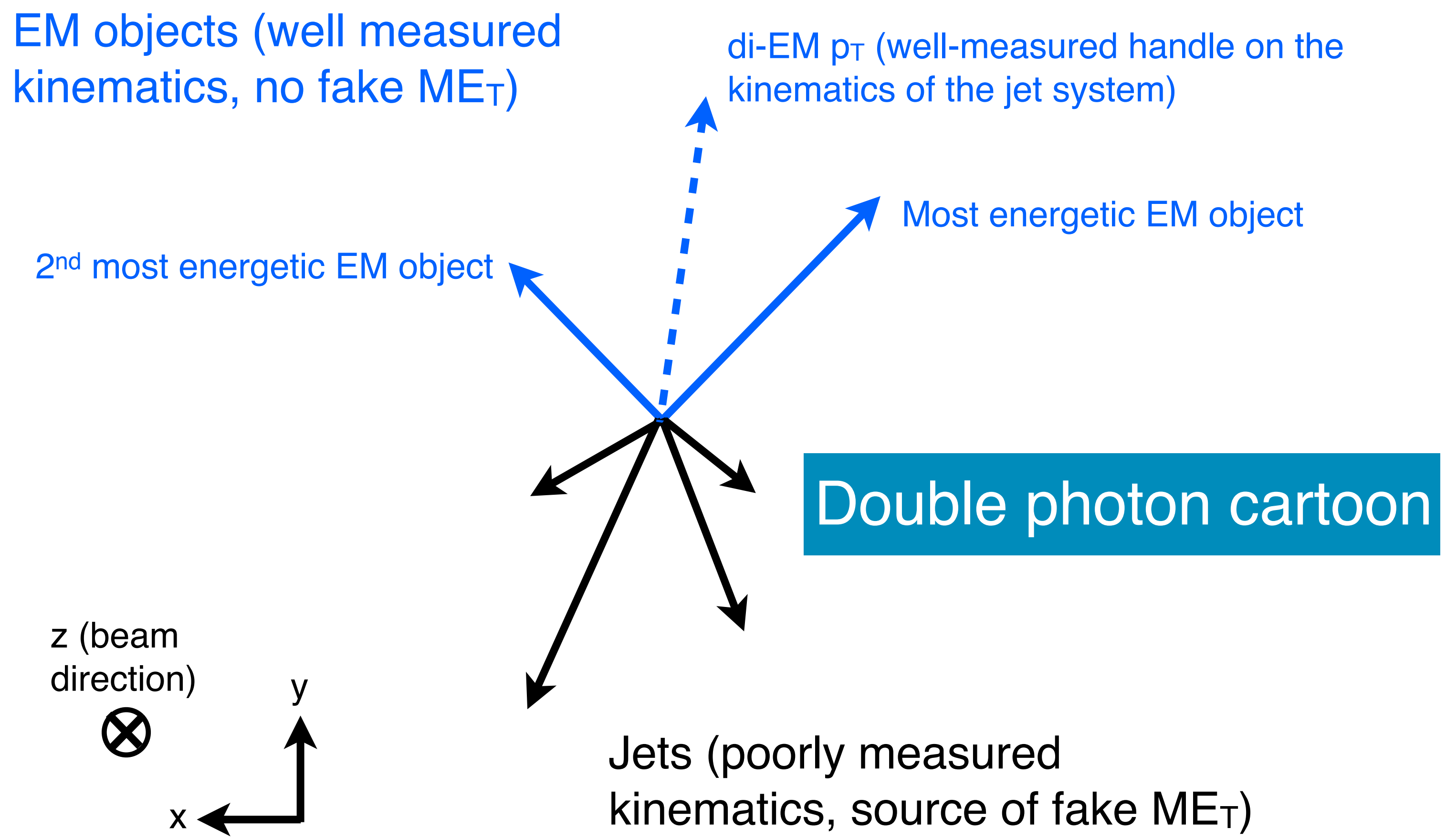
Topology	No. isolated photons	No. isolated leptons (e or μ)	No. jets
Double photon	≥2 with: •Leading $E_T > 45$ GeV •Trailing $E_T > 30$ GeV •$\|\eta\| < 1.4442$	No requirement	≥1 with: •$E_T > 30$ GeV •$\|\eta\| < 2.6$
Photon + lepton	≥1 with: •$E_T > 30$ GeV •$\|\eta\| < 1.4442$	≥1 with: •$E_T > 20$ GeV •$\|\eta\| < 2.1$	No requirement
Single photon	≥1 with: •$E_T > 75$ GeV •$\|\eta\| < 1.4442$	No requirement	≥3 with: •$E_T > 30$ GeV •$\|\eta\| < 2.6$ + $H_T^* > 400$ GeV

*H_T is the scalar sum of jet p_T in the event

Backgrounds: QCD

- Double photon
  - Dominant: **QCD with fake ME_T**
    - Multijet: at least 2 jets misidentified as photons
    - γ + jet: 1 jet misidentified as a photon
    - QCD diphoton
- Photon + lepton
  - Subdominant: **QCD with fake ME_T**
- Single photon
  - Dominant: **QCD with fake ME_T**
    - γ+jet
    - QCD multijet with at least 1 jet misidentified as a photon

Estimating the QCD background (1)



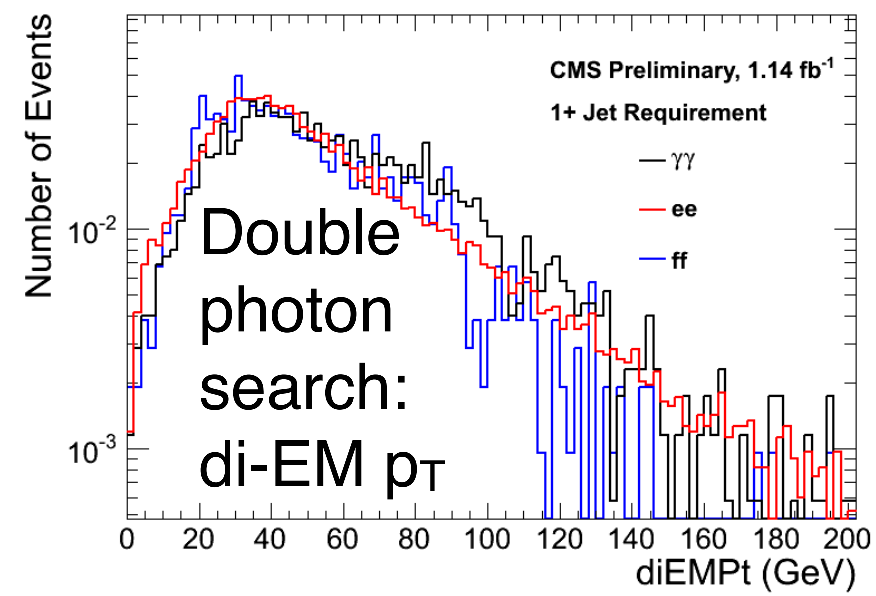
What is a well-measured EM object?

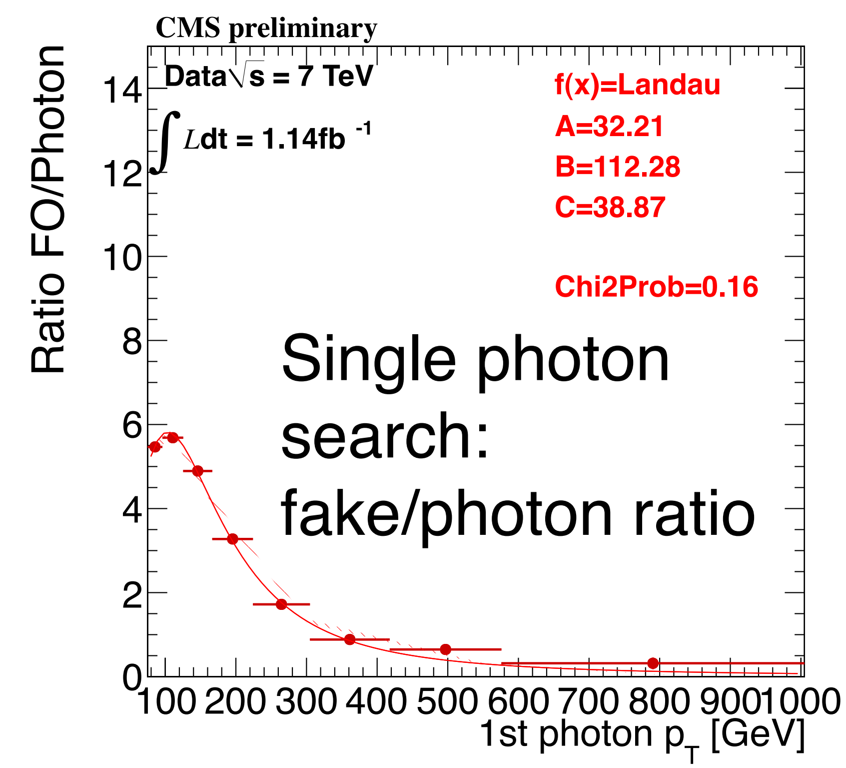
Di-electron	$Z \rightarrow e^+e^-$ decays "e" = γ + pixel match
Di-fake	Very electromagnetic di-jets (pixel match veto)
Single fake	1 very electromagnetic jet (pixel match veto)
Fake lepton + fake photon	Di-jets (well-isolated jet ["lepton"] + very electromagnetic jet ["photon"])

- **EM << hadronic** energy resolution ⇒ fake ME$_T$ due entirely to jet mismeasurement
- **Measure QCD background from data**—control sample with well-measured EM objects to model the QCD fake ME$_T$ spectrum
- **Reweight** ME$_T$ spectrum of control sample by p_T^{EM}(candidate)/p_T^{EM}(control)
- **Normalize** the predicted QCD fake ME$_T$ spectrum to a signal-depleted **low-ME$_T$ region**

Estimating the QCD background (2)

- **Double photon**:
  - **Di-electron** and **di-fake** control samples
  - Reweight by **di-EM p_T**
  - Normalize in $ME_T < 20$ GeV region
- **Single photon**:
  - **Single fake** control sample
  - Reweight by ratio **(candidate photon p_T/fake p_T)**
  - Normalize in $ME_T < 100$ GeV region
- **Photon + lepton**:
  - **Di-electron** and **fake lepton + fake photon** control samples
  - Reweight by **di-EM p_T and p_T^l**
  - Normalize in $ME_T < 30$ GeV region



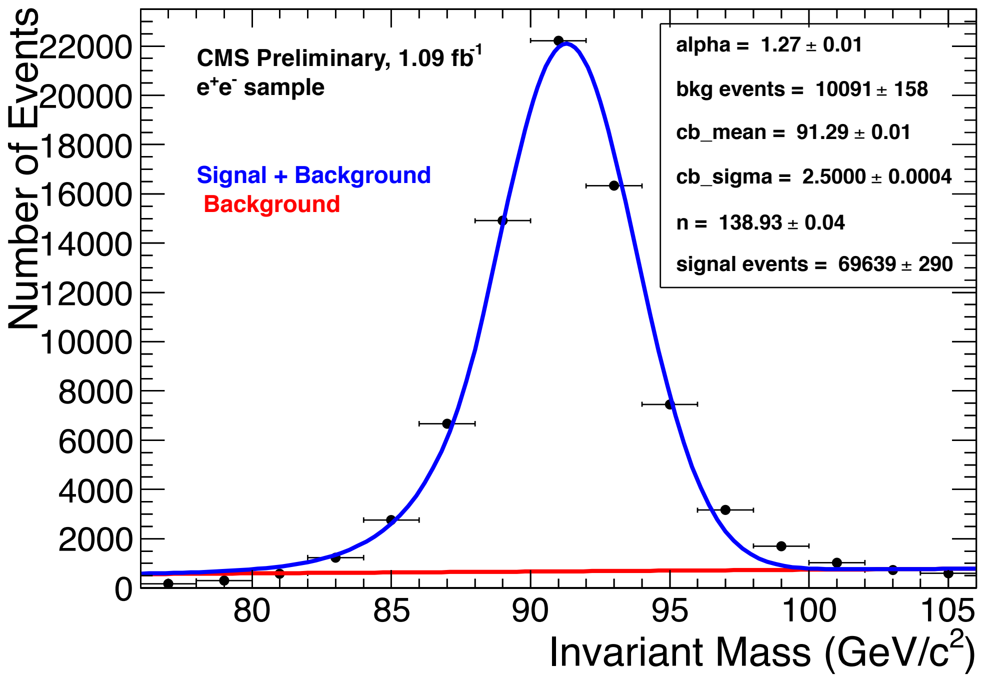


Backgrounds: electroweak

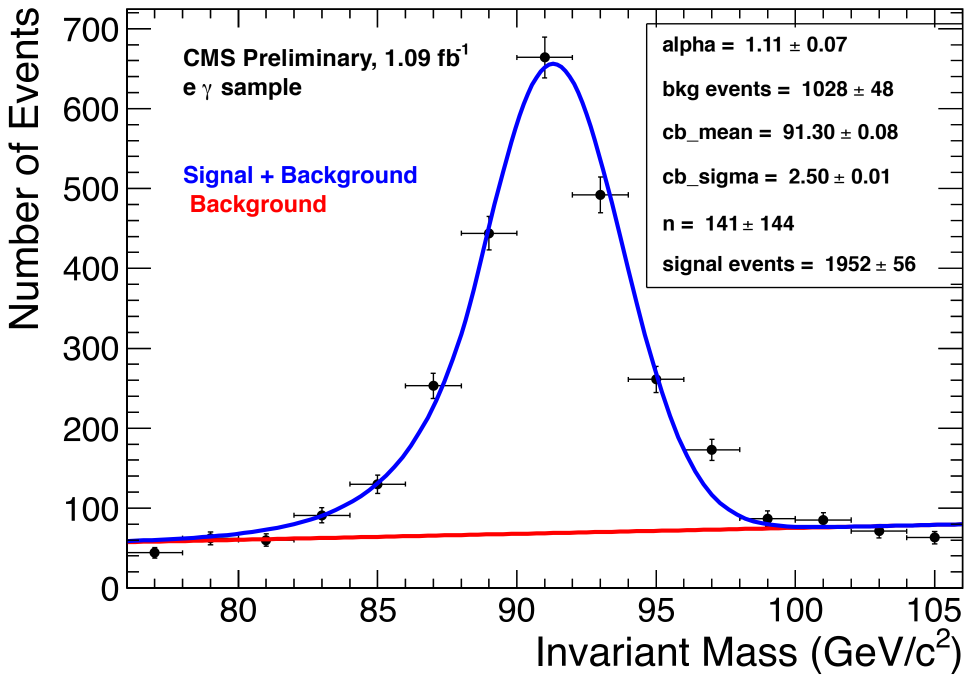
- Double photon
  - Subdominant: **electroweak processes with real ME_T**
    - $W(\rightarrow e\nu)\gamma$: electron misidentified as a photon
    - $W(\rightarrow e\nu)$+jet: electron and jet misidentified as photons
- Photon + lepton
  - Subdominant: **jets faking photons in events with real ME_T**
    - $W(\rightarrow e\nu)$+jet, $W(\rightarrow \mu\nu)$+jet
  - Subdominant: **electrons faking photons**
    - $Z\rightarrow ee$
    - ttbar with at least 1 W decaying to an electron
- Single photon
  - Subdominant: **electroweak processes with real ME_T**
    - $W\rightarrow e\nu$, $Z\rightarrow ee$, or ttbar semileptonic with 1 electron misidentified as a photon

Estimating the electroweak background

- Estimate the **electron→photon mis-ID rate $f_{e\to\gamma}$** by fitting the di-EM invariant mass spectra in the di-electron and eγ samples
- Scale the ME_T distribution of an appropriate **electron control sample** by $f_{e\to\gamma}$
  - Double photon search: **eγ** sample (2 objects passing the candidate photon ID criteria; 1 with pixel match [e], 1 with pixel match veto [γ])
  - Single photon search: **single e** sample (e as above) weighted by γ/e p_T ratio as on slide 12
  - Photon + lepton search: **lepton + e** (e as above) sample
- Estimate the **jet→photon mis-ID background** by scaling a **lepton + "fake photon" control sample** by jet→photon mis-ID rate (photon + lepton search only)



Di-electron sample



eγ sample

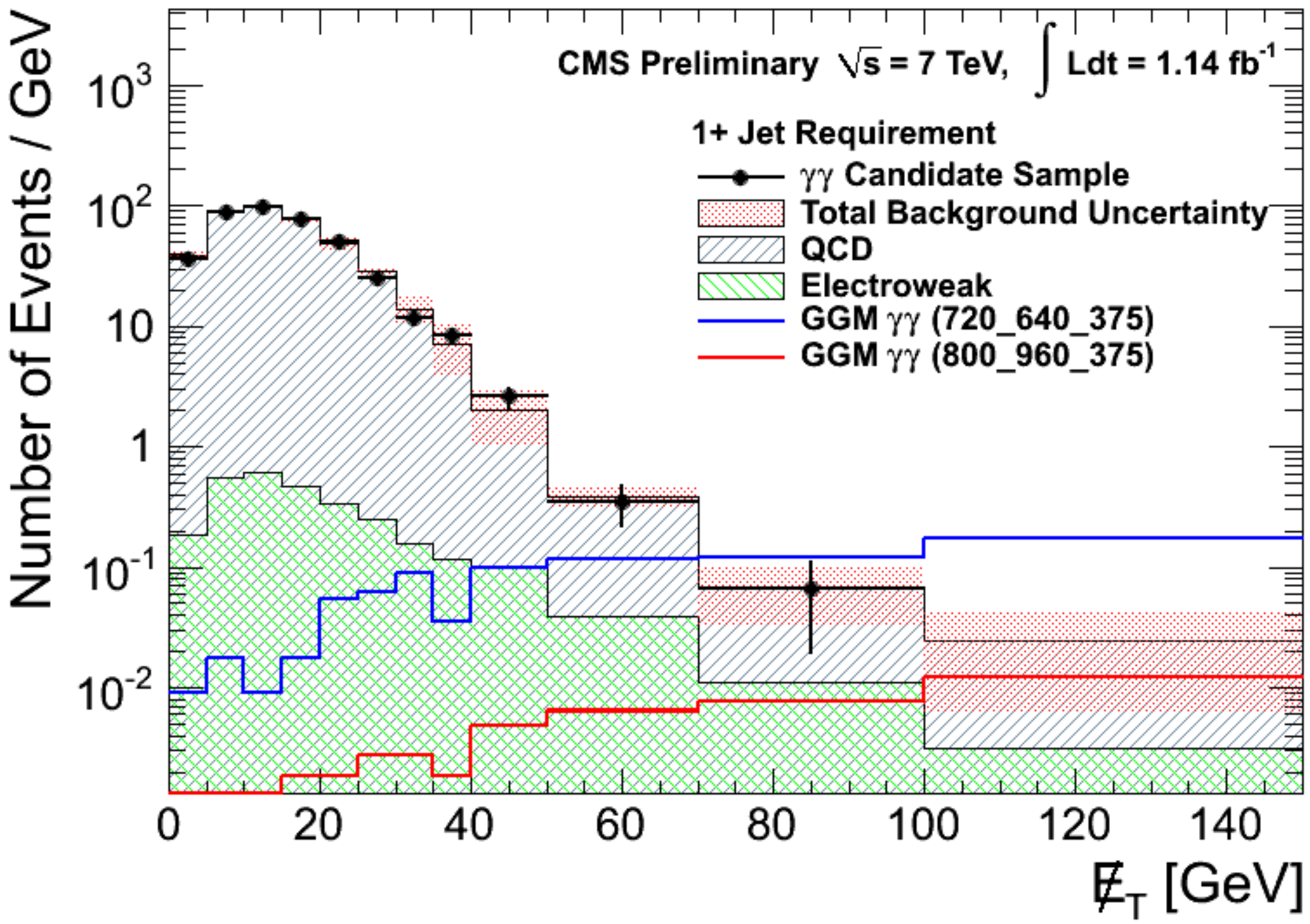
Stat. ⊕ fit ⊕ syst.(p_T dependence)

$f_{e\to\gamma} = 0.014 \pm 0.002$

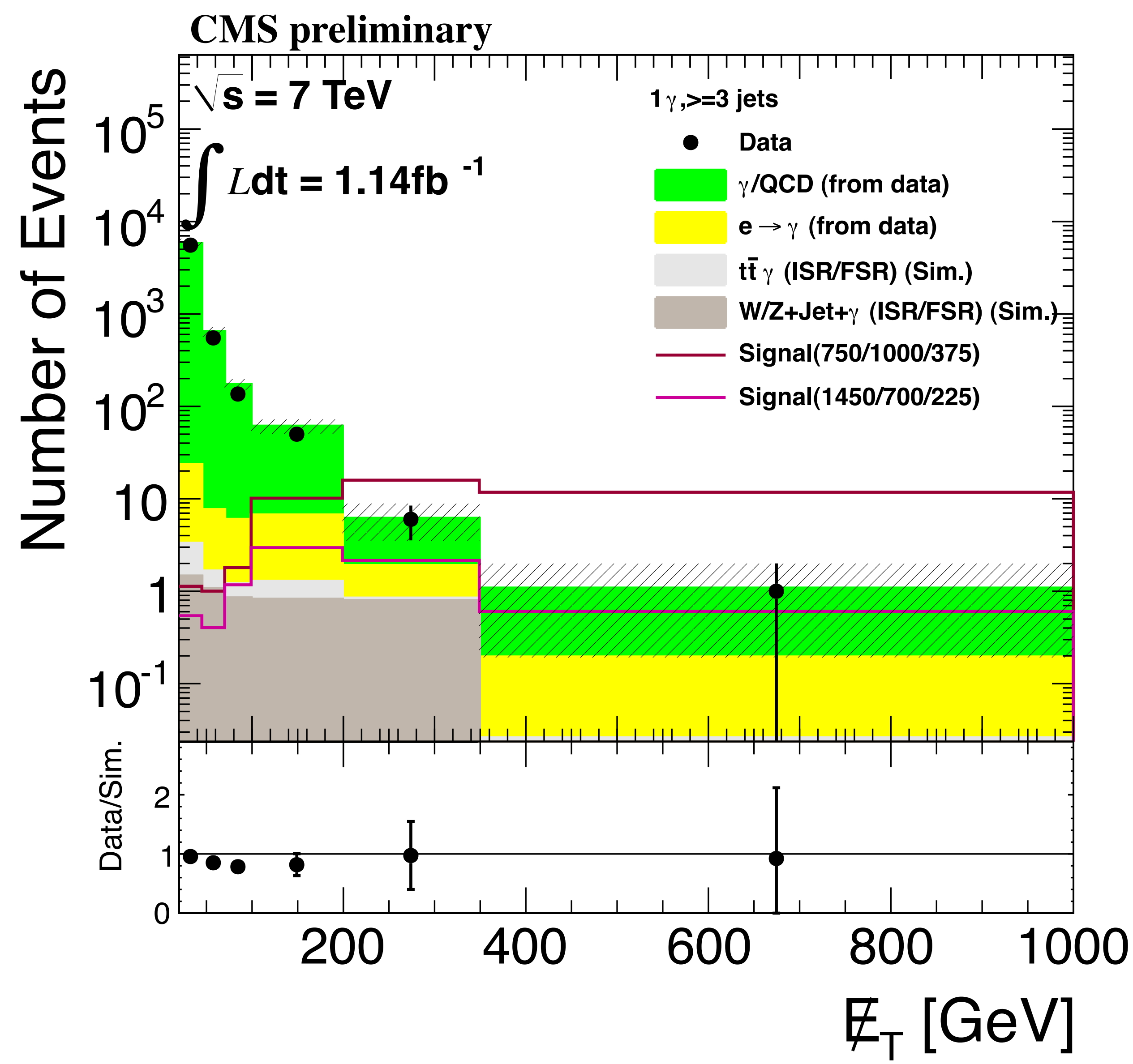
Backgrounds: MC

- Double photon
  - Negligible: irreducible backgrounds
    - Wγγ (total cross section ~7 fb at 14 TeV LHC) [6]
    - Zγγ
- Photon + lepton
  - Dominant: **W(→eν)γ, W(→μν)γ**
    - MadGraph tune D6T, BAUR NLO, K-factors range ~2-3
  - Negligible: ttbar+γ
- Single photon
  - Subdominant: initial state radiation (ISR) or final state radiation (FSR) of photons in events with no electron (e.g. ttbar/W/Z→hadrons)
    - Pythia MC with 100% uncertainty (contribution very small)

Candidate ME_T spectra (1)



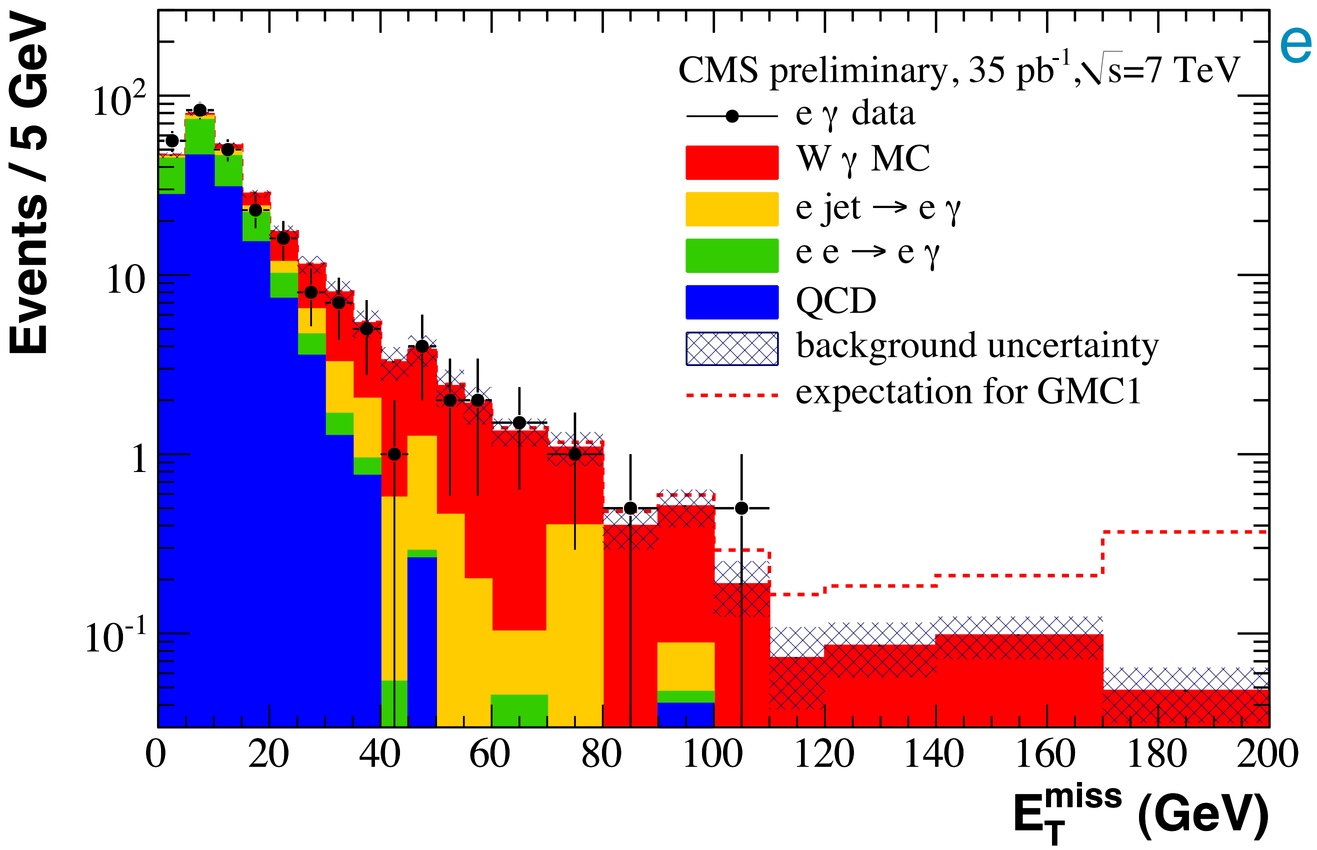
Double photon search



Observed events consistent with predicted background

Single photon search

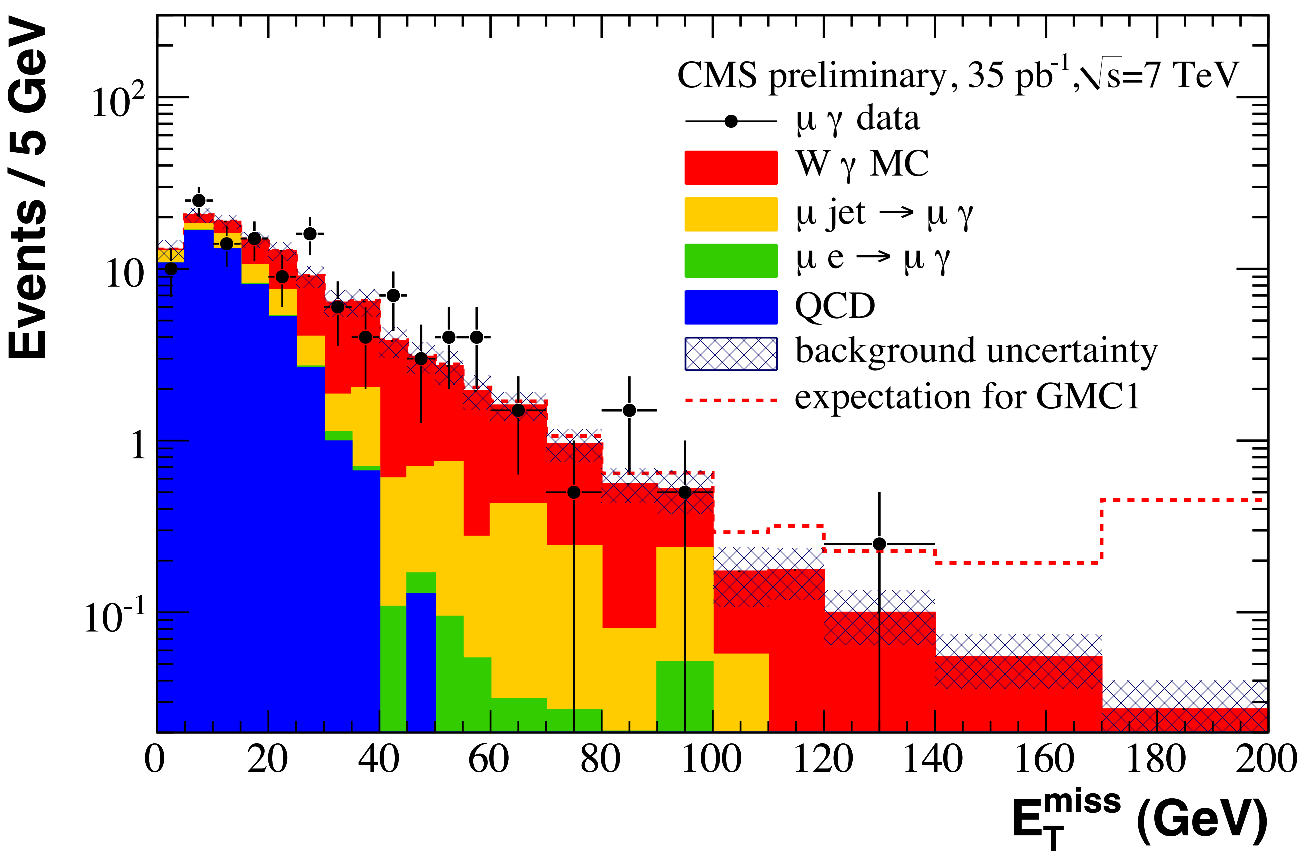
Candidate ME_T spectra (2)



e+γ+ME_T

Example GGM model:
$m_{\tilde{g}} = m_{\tilde{q}} = 450$ GeV, $m_{\tilde{\chi}_1^0} \approx m_{\tilde{\chi}_1^+} = 195$ GeV

μ+γ+ME_T



Observed events consistent with predicted background

Upper limit calculation

- “Simplified model” GGM signal MC [7]
  - Next to leading order production cross-sections calculated with PROSPINO 2.1
  - Pythia 6.422 for hadronization and decay
  - Full CMS detector simulation based on GEANT
  - PDF uncertainties calculated using PDF4LHC recommendations [8]
  - 3 different NLSP scenarios

$\gamma\gamma$ + ME_T, γ + ME_T →

1. **Bino NLSP: M_1 = 375 GeV, M_2 = 3.5 TeV**, tan β = 2, squark and gluino masses in [400 GeV, 2000 GeV], sleptons and all gauginos except the lightest neutralino have mass 3.5 TeV, heavy right-handed squarks (GGM sum rules)

γ + ME_T →

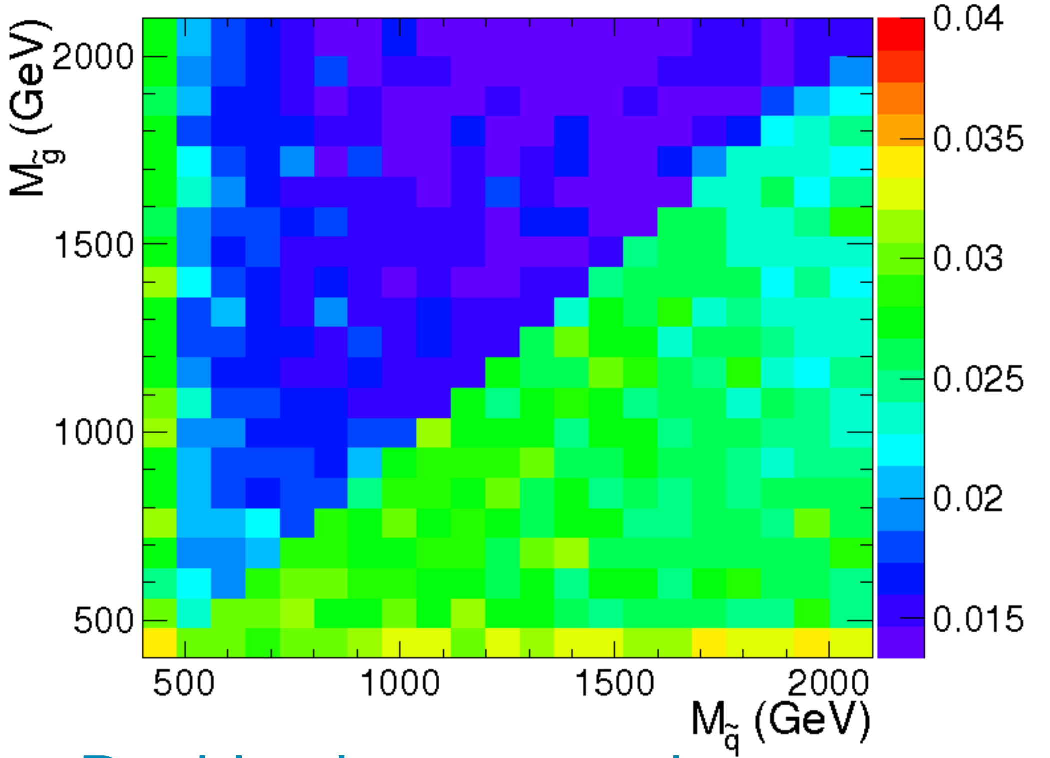
2. **Wino NLSP (1): M_1 = 3.5 TeV, M_2 = 375 GeV**, tan β = 2, squark and gluino masses in [400 GeV, 2000 GeV], sleptons and all gauginos except the lightest neutralino and chargino have mass 3.5 TeV, heavy right-handed squarks (GGM sum rules)

γ + l + ME_T →

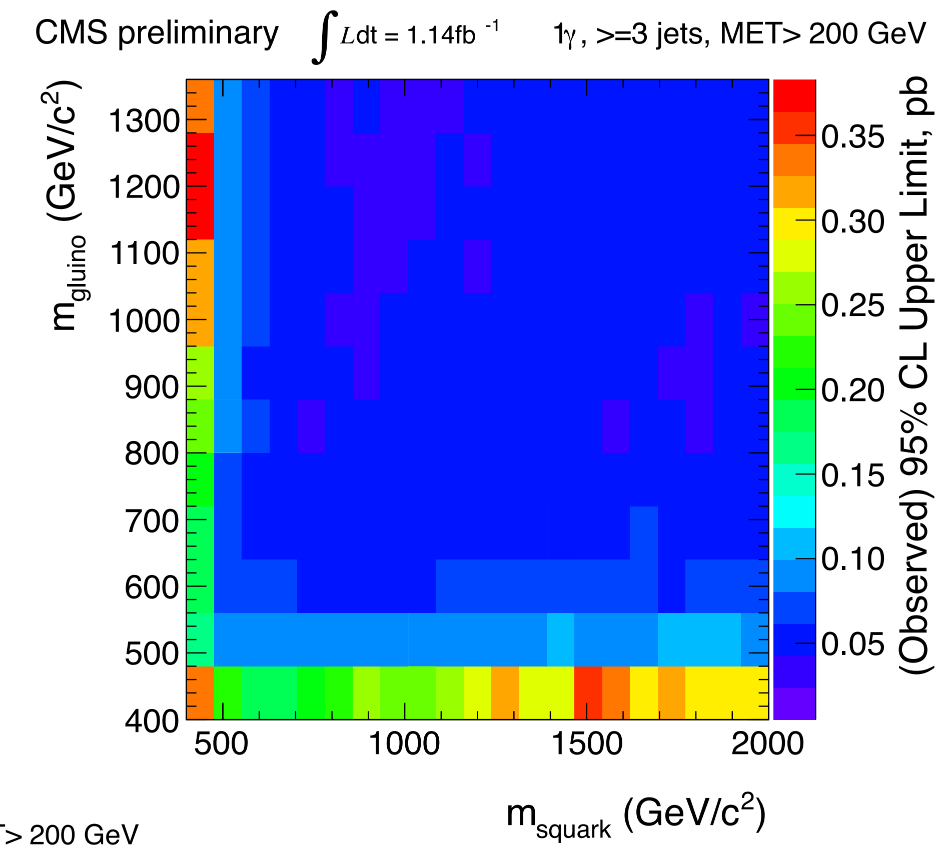
3. **Wino NLSP (2): $m_{squark} \sim m_{gluino}$**, tan β = 2, NLSP mass > 100 GeV

- CL_S upper limit calculation for scenarios 1 and 2 [9], Bayesian upper limit calculation with flat prior [10] for scenario 3

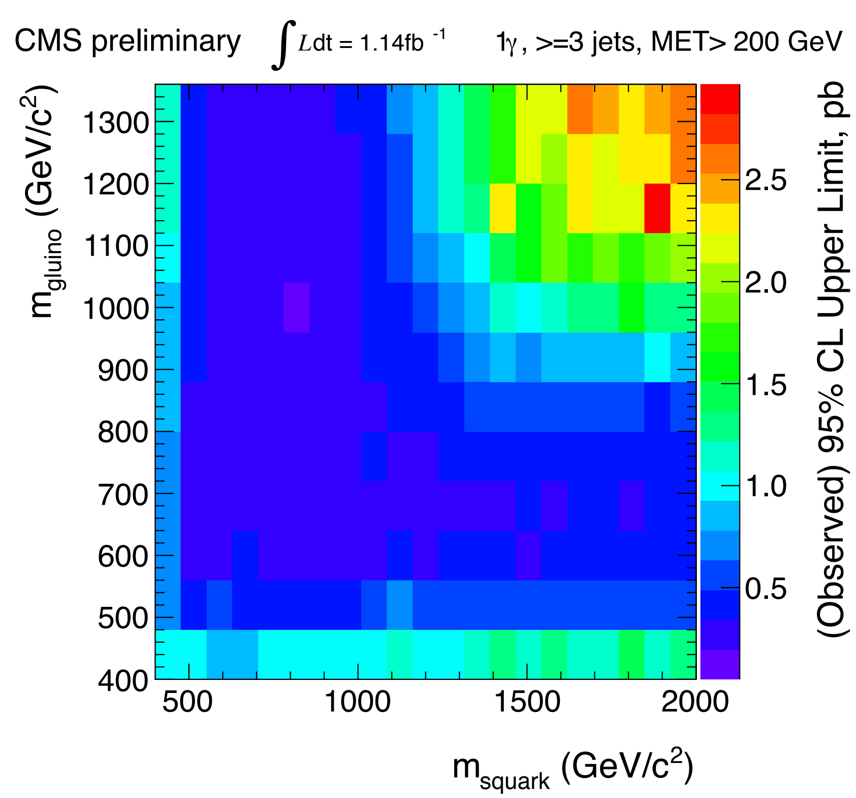
Upper limits



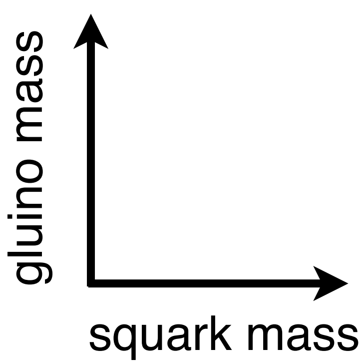
Double photon search
Bino NLSP



Single photon search
Bino NLSP

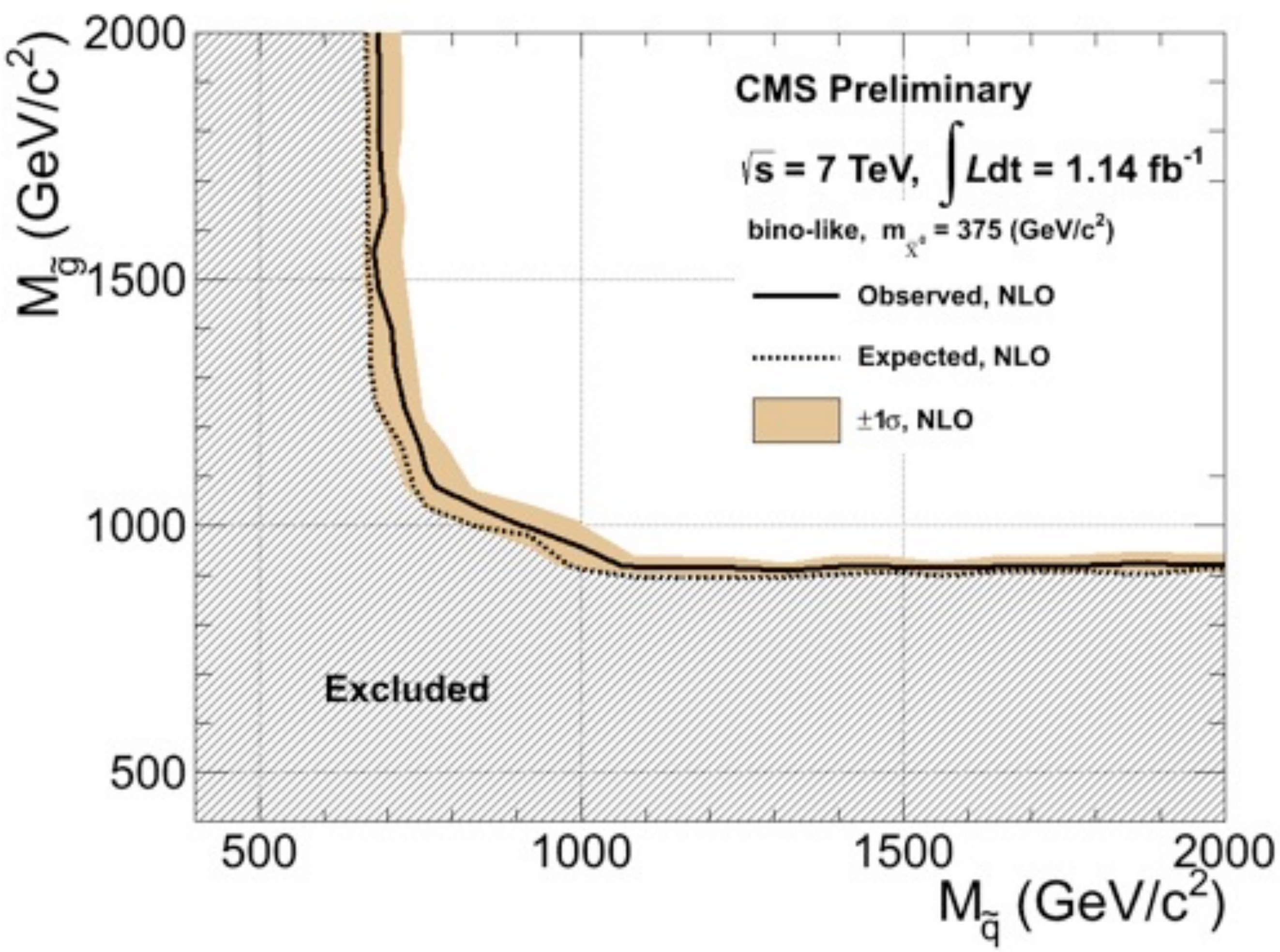


Single photon search
Wino NLSP

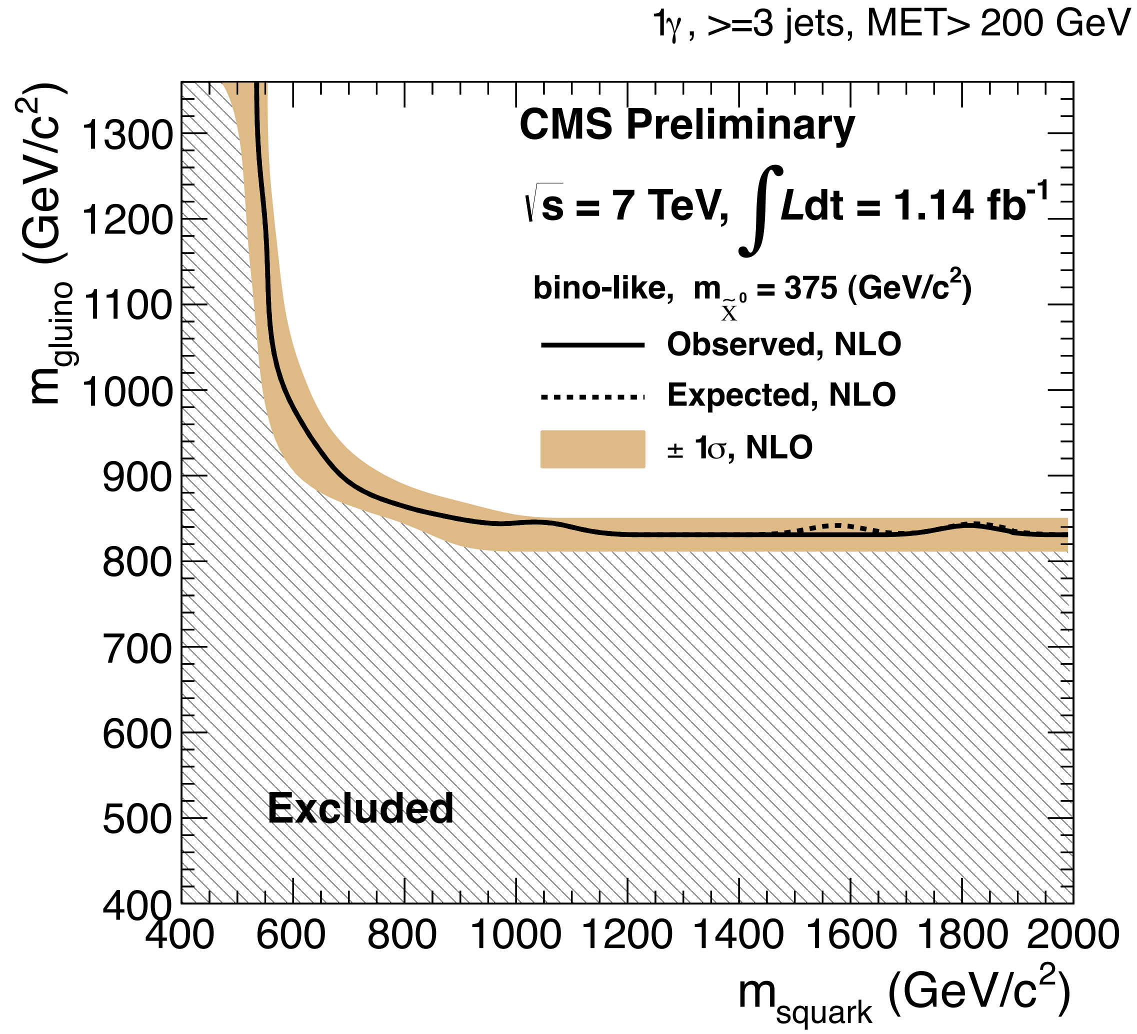


Exclusion contours for bino NLSP

Double photon search



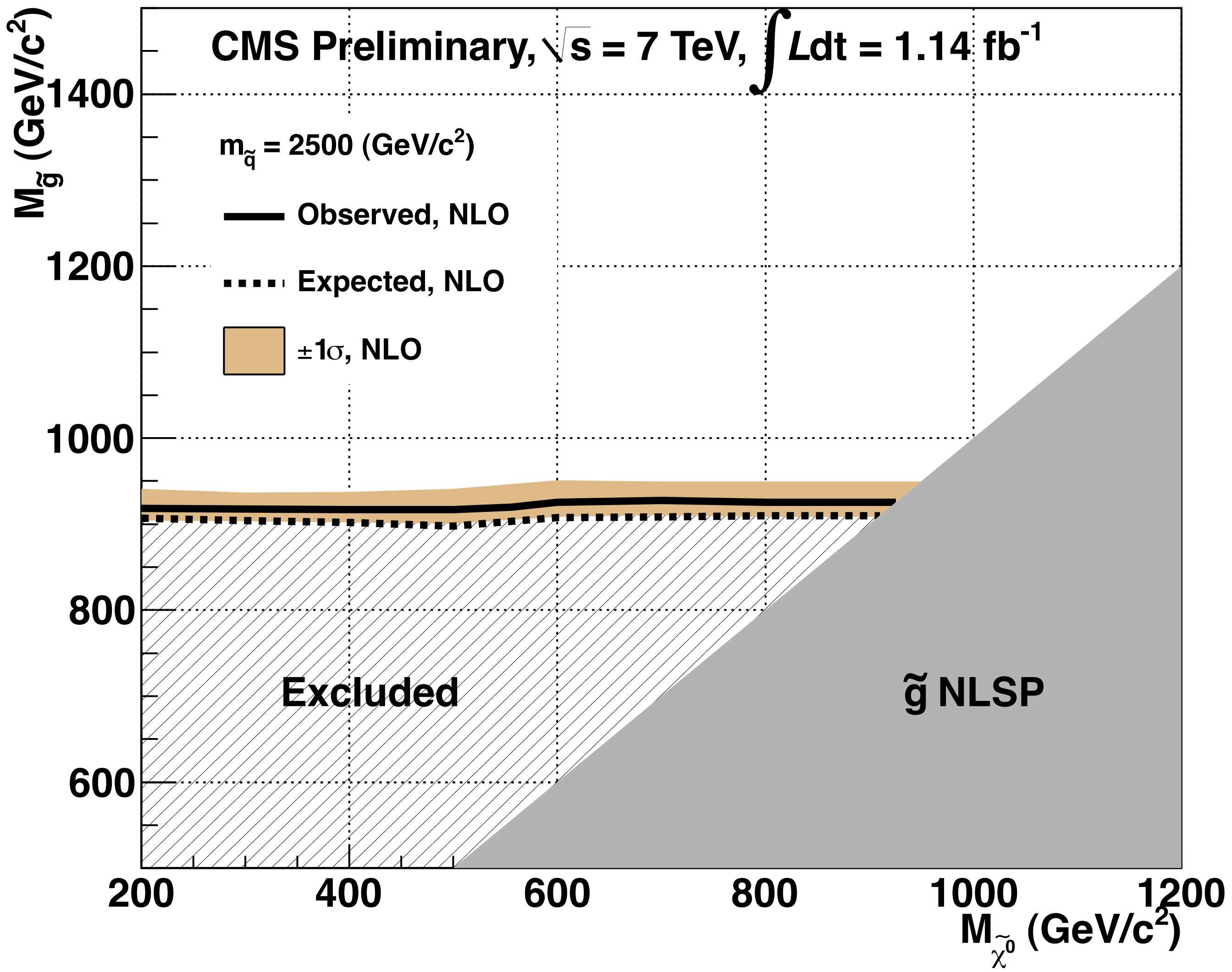
Single photon search



Search region	No. expected	No. observed
$\gamma\gamma$ + ≥1j + (ME_T > 100 GeV)	1.5 ± 0.8(stat.) ± 0.6(syst.)	0
γ + ≥3j + (ME_T > 200 GeV)	7.24 ± 2.6(stat.) ± 1.53(syst.)	7

Bino NLSP exclusion in the m_{gluino}-$m_{neutralino}$ plane

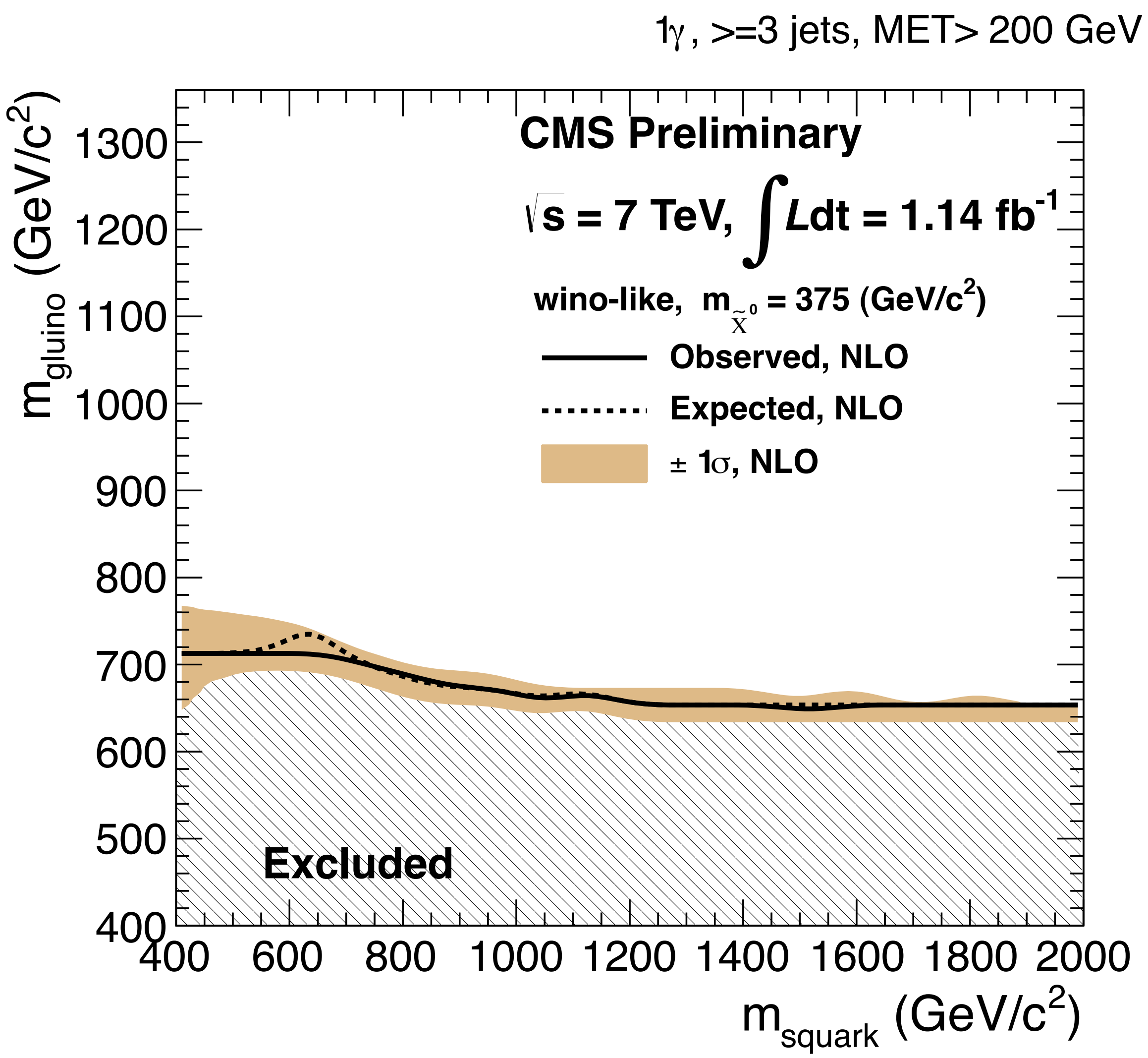
Brand new for SUSY11!



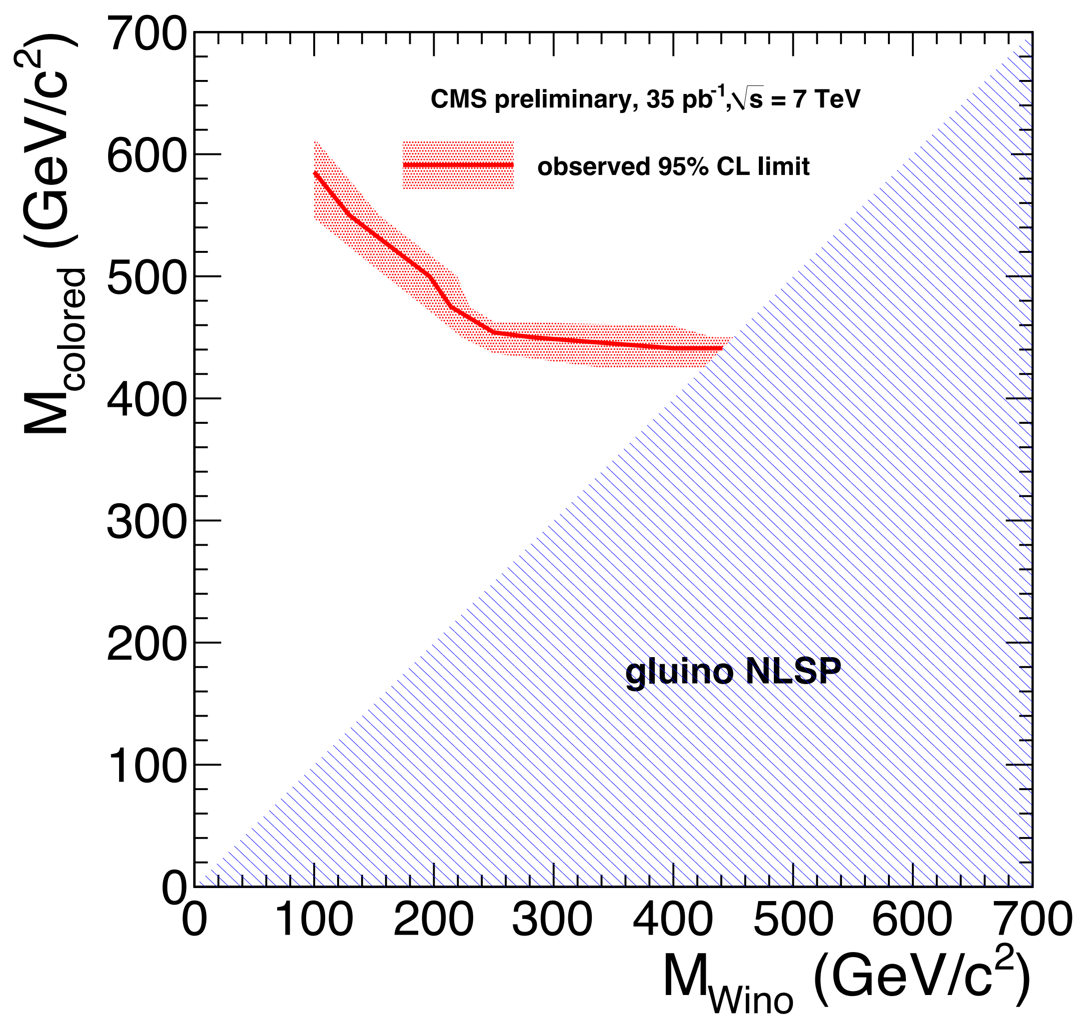
- Double photon search
- m_{squark} = 2.5 TeV
- Exact same analysis, exclusion just plotted in a different plane

Exclusion contours for wino NLSP

Single photon search

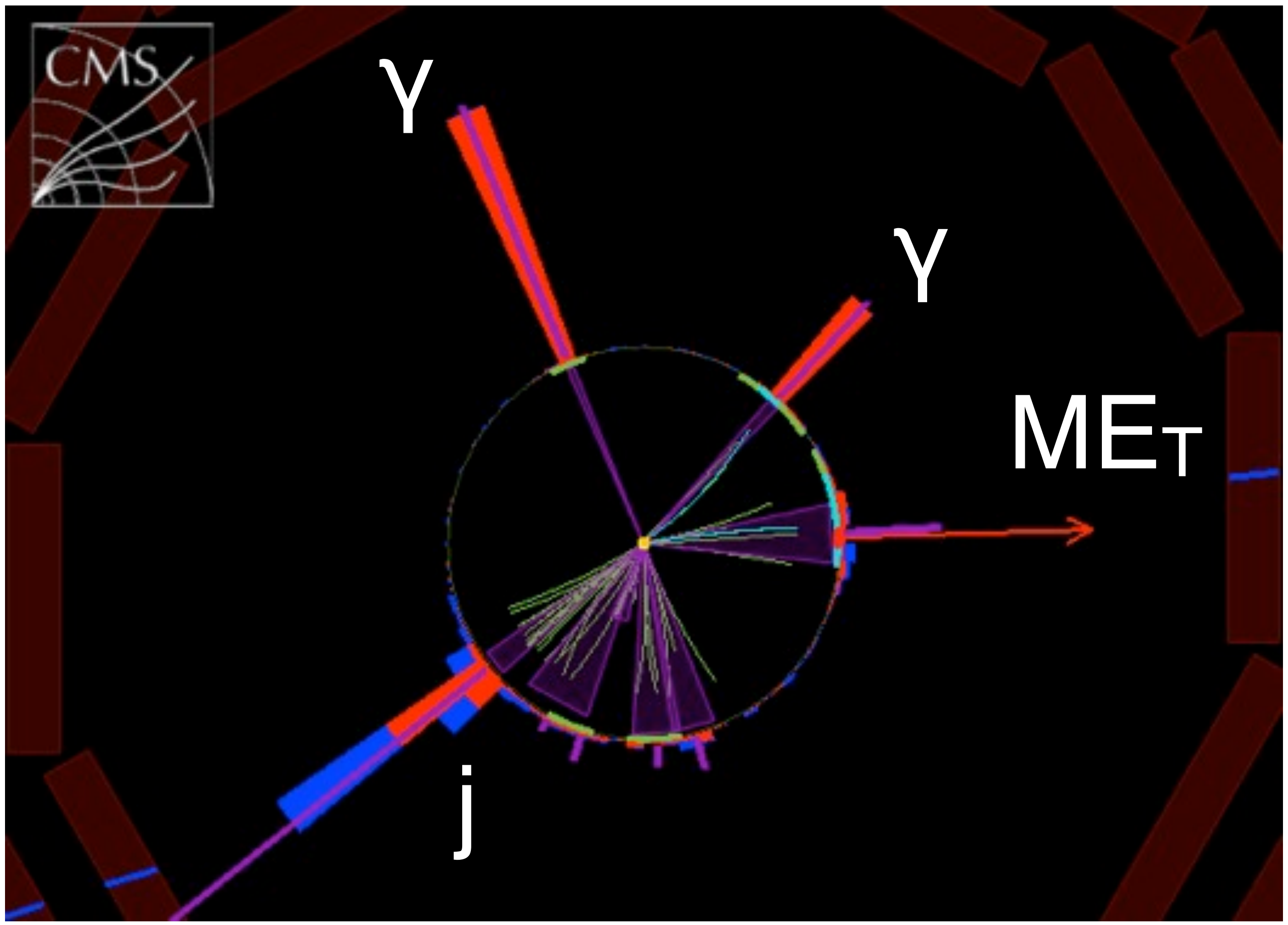


Photon + lepton search



Search region	No. expected	No. observed
γ + e + (ME_T > 100 GeV)	1.74 ± 0.43(stat. ⊕ syst.)	1
γ + μ + (ME_T > 100 GeV)	1.59 ± 0.39(stat. ⊕ syst.)	1
γ + ≥3j + (ME_T > 200 GeV)	7.24 ± 2.6(stat.) ± 1.53(syst.)	7

Conclusions

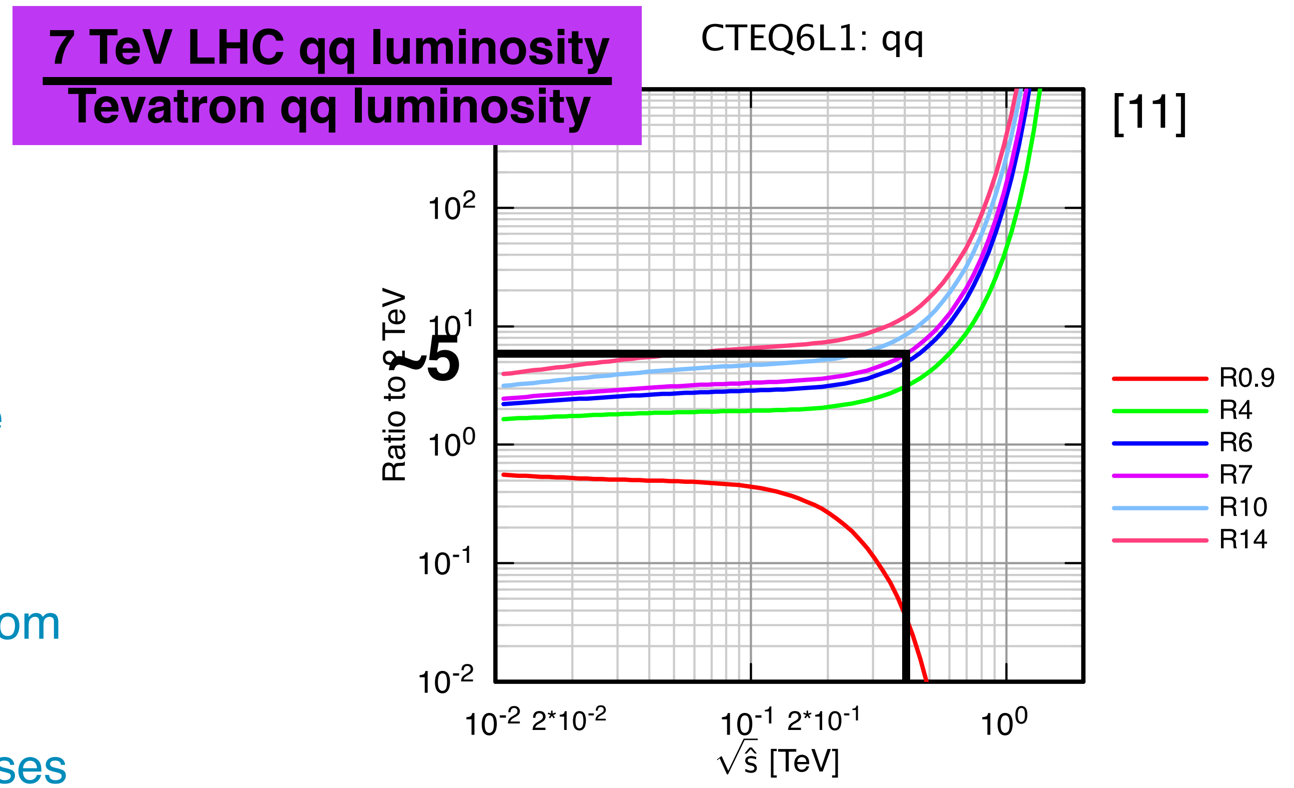


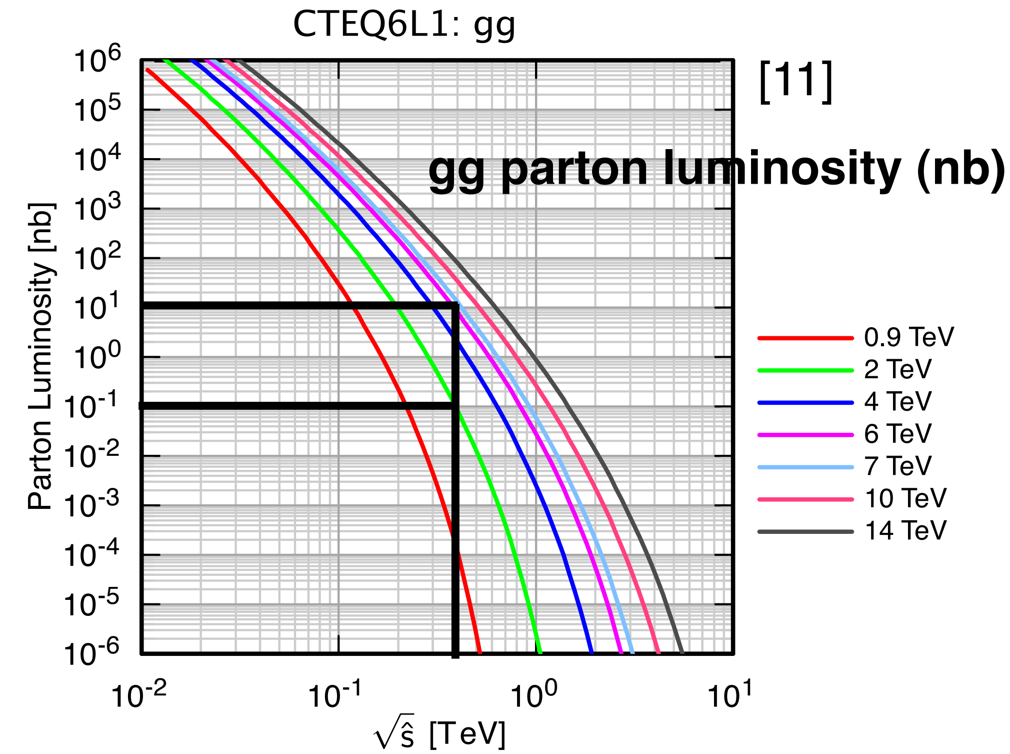
CMS simulation
m_{squark} = 1.25 TeV, m_{gluino} = 1.2 TeV, $m_{neutralino}$ = 225 GeV

- Searches in double photon, single photon, and photon + lepton final states are powerful tools for observing SUSY
  - Clean trigger objects
  - Manageable backgrounds that can mostly be estimated from data
- CMS actively searching for gauge-mediated SUSY in a variety of ways
  - In the **classic bino NLSP scenario, $m_{squark} = m_{gluino} \sim$ 950 GeV** excluded
  - In the **wino NLSP scenario, $m_{gluino} \sim$ 650 GeV** excluded ~independently of m_{squark} and m_{wino}

Backup

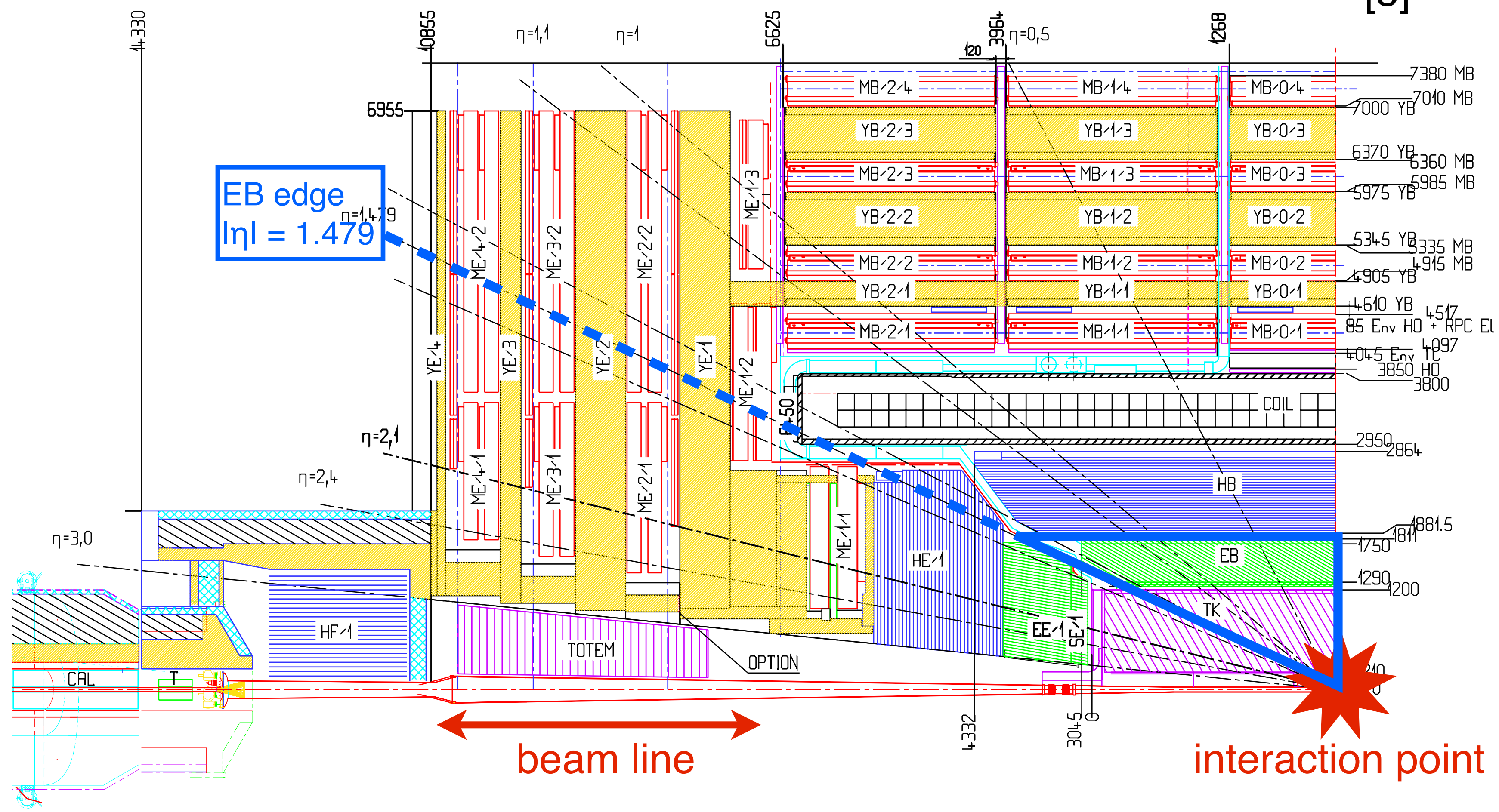
- General gauge mediation (GGM)
  - P. Meade, N. Seiberg, and D. Shih, Prog. Theor. Phys. Suppl. **177** (2009) 143 (arXiv:0801.3278v3 [hep-ph])
  - Definition of gauge mediation: the MSSM and the SUSY-breaking sector are linked only by nonzero values of the MSSM gauge coupling constants
  - Different theories of gauge mediation can arise from the single general framework
  - Prescription provided for calculating the soft masses of the spectrum
  - SUSY-breaking sector leads to mass relations between the sfermions, constraining the allowed parameter space
- Consequences for phenomenology
  1. **Enhancement of gg parton luminosity at the LHC with respect to quark-antiquark ⇒ can quickly probe models with light colored particles**
  2. **Lightest neutralino NLSP can be bino, wino, or higgsino, leading to distinct and exotic LHC final states**





Photons

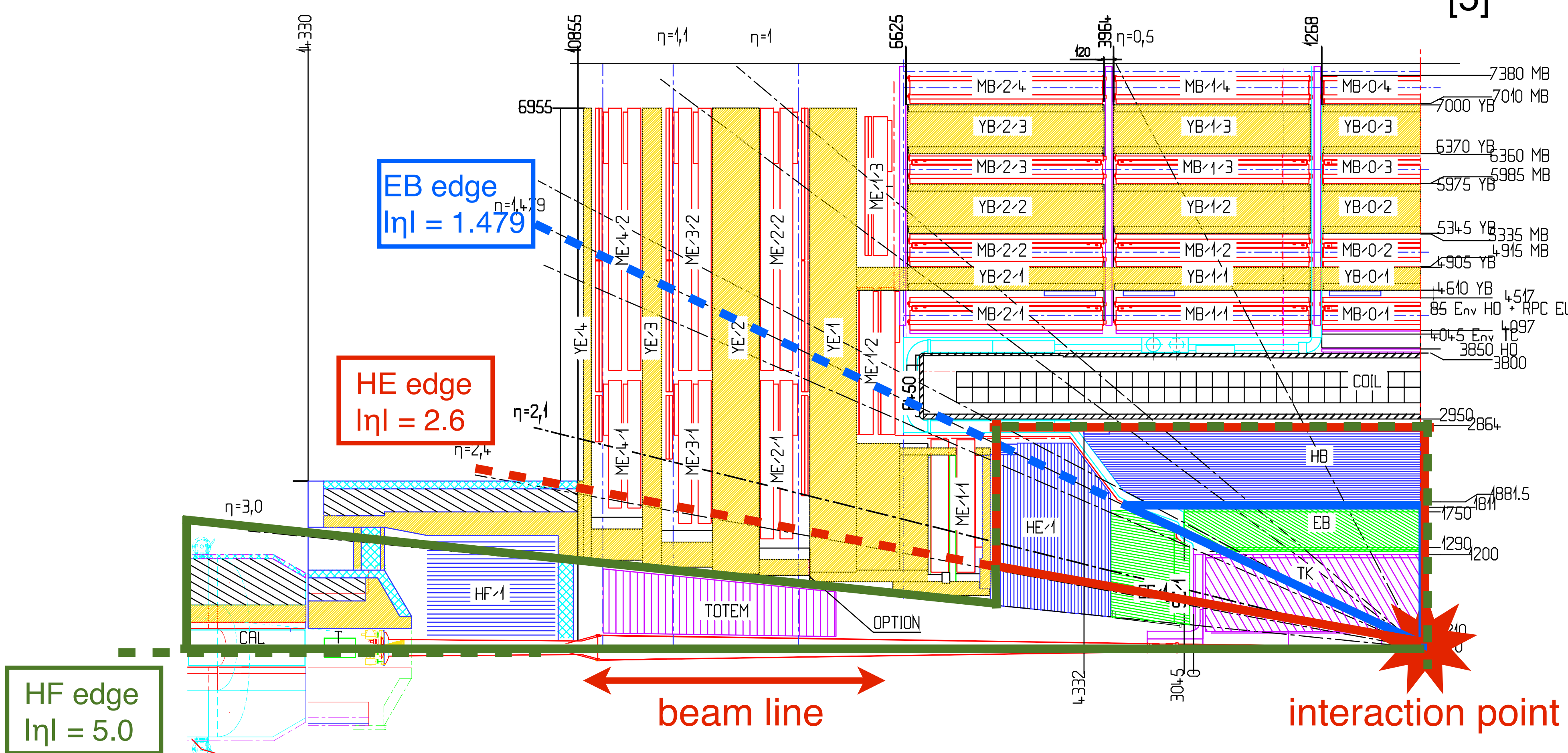
[5]



- Photons
  - Isolated from jets
    - Tracker and calorimeter isolation + electromagnetic calorimeter (ECAL) shower shape variables reject photons within jets (i.e. from π^0 decay)
    - Ratio of energy in the hadronic calorimeter (HCAL) directly behind the photon candidate to ECAL energy rejects jets that have begun to shower in the ECAL
  - Inconsistent with ECAL noise
  - No matching hit in the silicon pixel detector

Jets and ME_T

[5]



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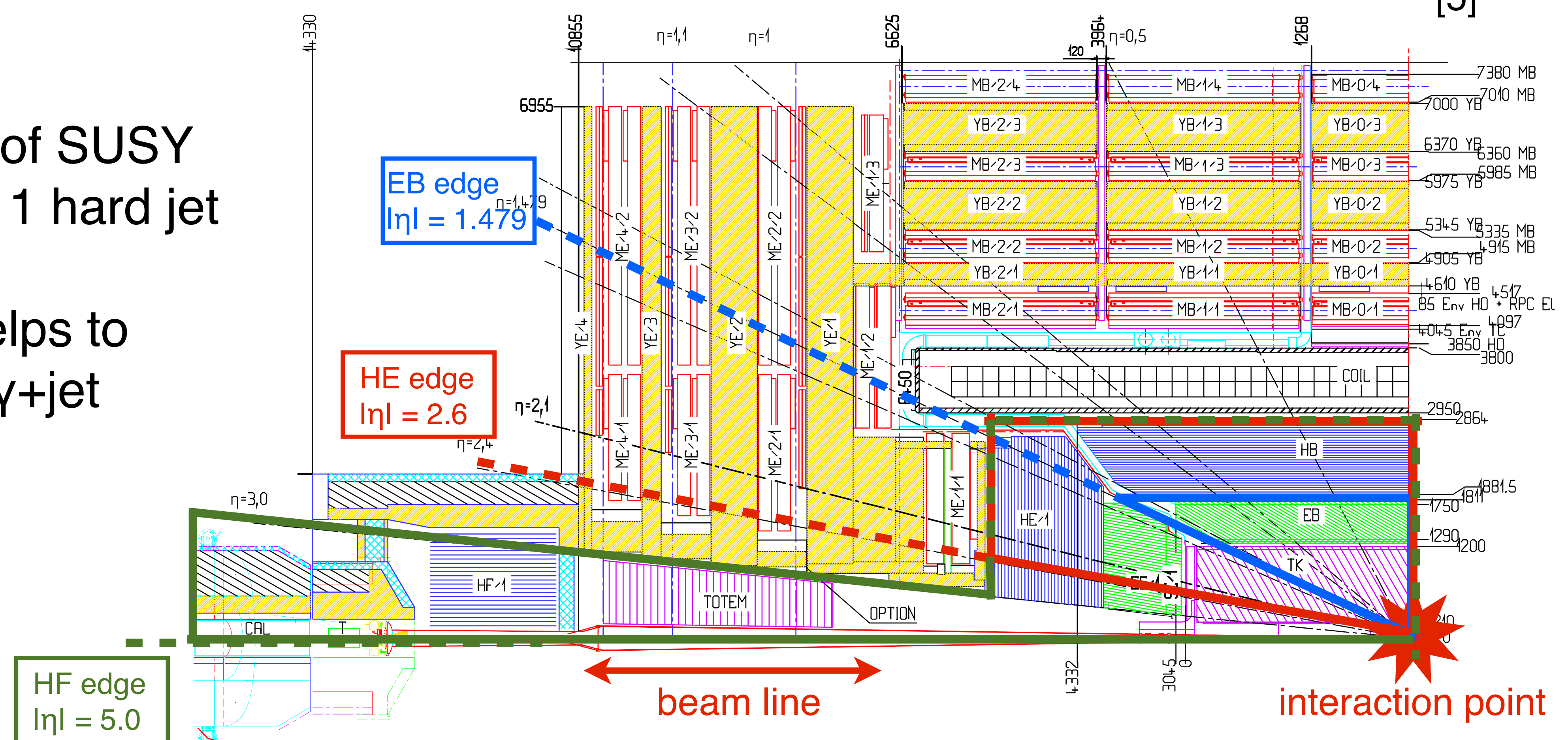
- Jets and ME_T
  - Particle-flow (PF) jets (anti-k_T algorithm with R = 0.5)
  - Inconsistent with HCAL noise
  - Corrected for pileup, p_T response, and η response
  - PF ME_T built from PF tracks and calorimeter clusters with jet corrections applied

Jets and ME_T

[5]

Why jets?

- Strong production of SUSY guarantees at least 1 hard jet per event
- Jet requirement helps to suppress dijet and γ+jet backgrounds



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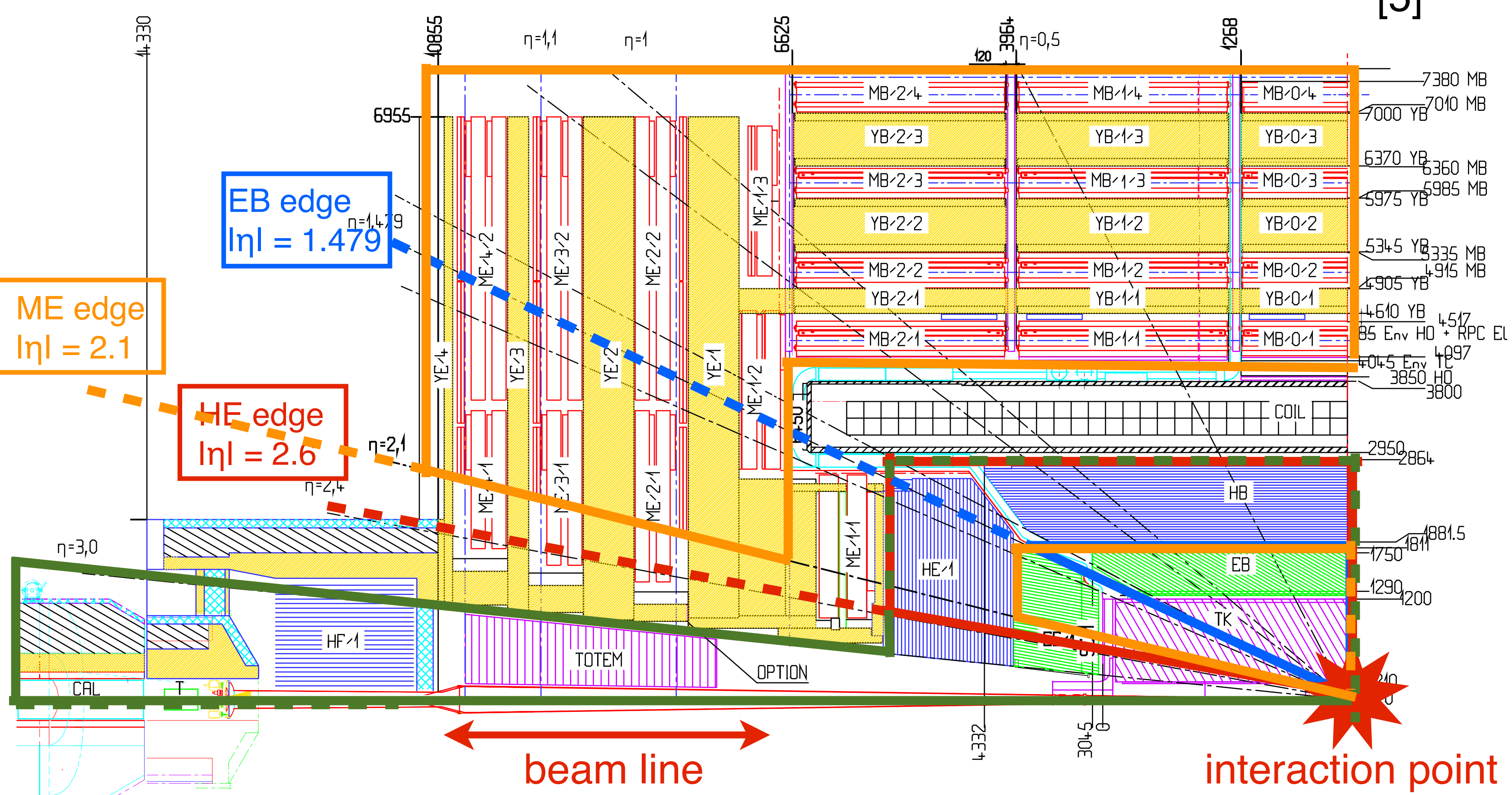
Electrons and muons

- Leptons
  - Electrons
    - Isolated from jets (similar to photon isolation)
    - Inconsistent with ECAL noise
    - Good quality track match to ECAL cluster
    - Inconsistent with photon conversion
    - Within barrel muon trigger acceptance
  - Muons:
    - Isolated from jets (similar to photon isolation)
    - Good quality track
    - Matched to trigger object
    - Within barrel muon trigger acceptance



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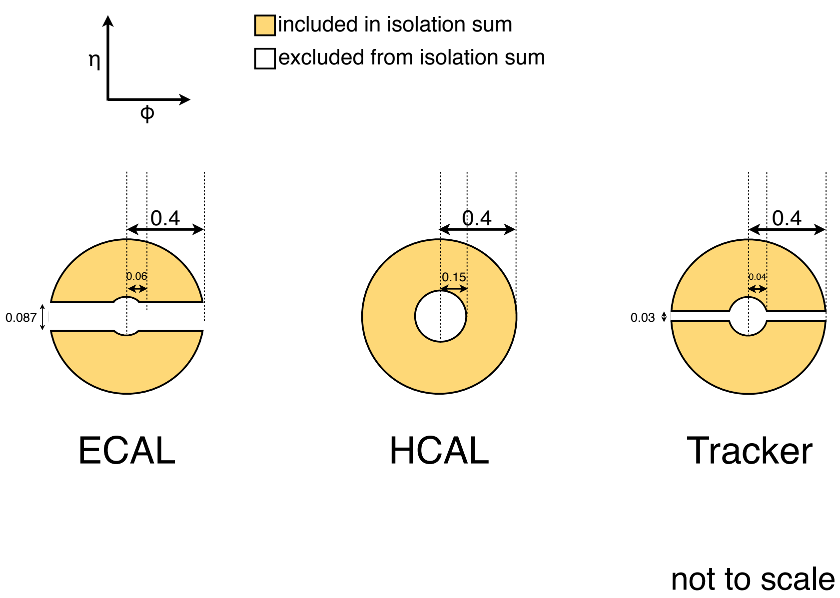
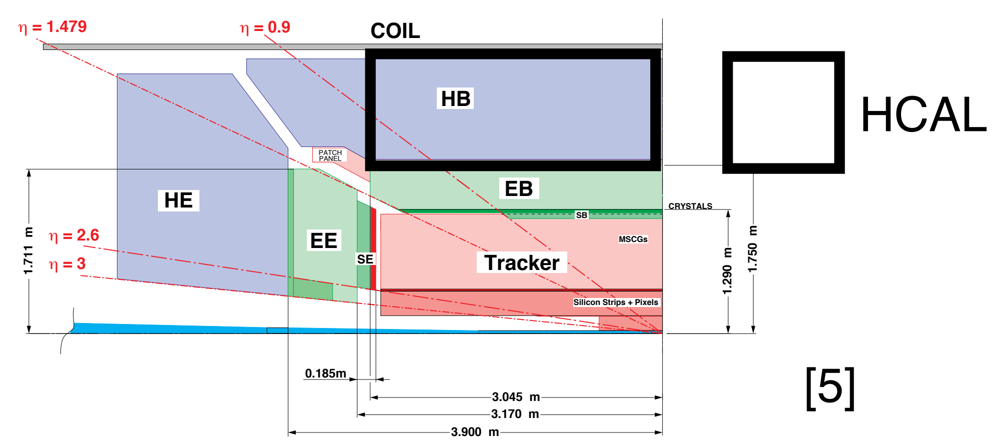
Photon isolation criteria

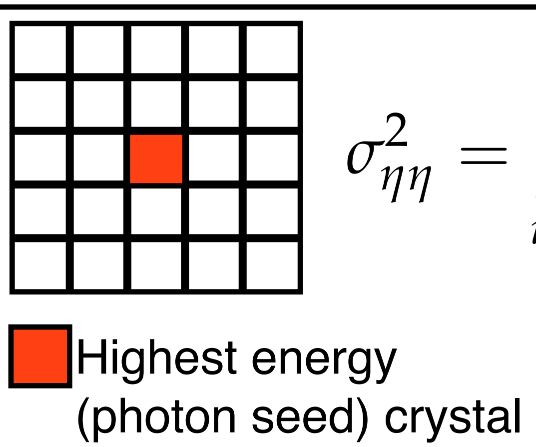


- ECAL isolation energy < $0.006E_T$ + 4.2 GeV
- HCAL isolation energy < $0.0025E_T$ + 2.2 GeV
- Tracker isolation energy < $0.001E_T$ + 2.0 GeV

$$\frac{\text{HCAL energy in } R < 0.15 \text{ cone around photon candidate}}{\text{ECAL energy of photon candidate}} < 0.05$$



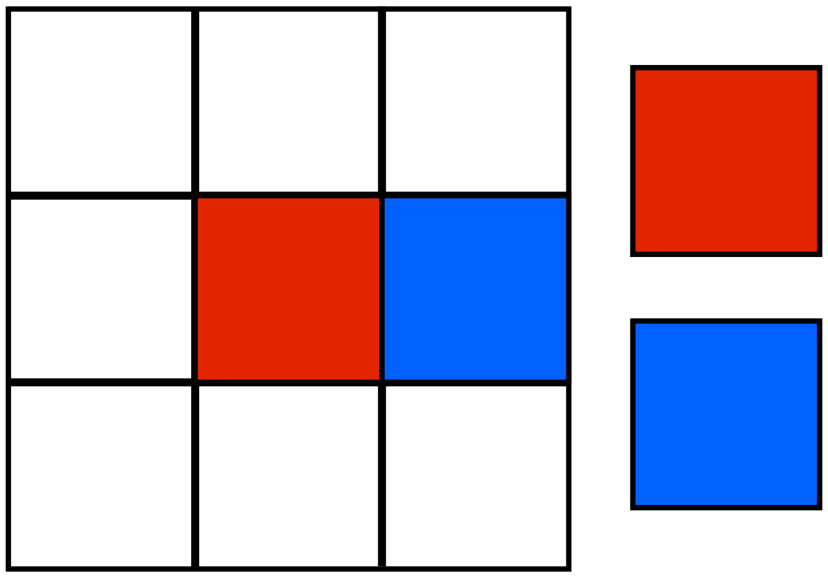
[5]



$$\sigma^2_{\eta\eta} = \sum_{i=1}^{25} w_i(\eta_i - \bar{\eta})^2 / \sum_{i=1}^{25} w_i, \quad < 0.011$$

where $w_i = \max(0, 4.7 + \ln(E_i/E))$, E_i is the energy of the i^{th} crystal in a group of 5×5 centred on the one with the highest energy, and $\eta_i = \hat{\eta}_i \times \delta\eta$, where $\hat{\eta}_i$ is the η index of the ith crystal and $\delta\eta = 0.0174$; E is the total energy of the group and $\bar{\eta}$ the average η weighted by w_i in the same group [20]. [12]

ECAL noise cleaning



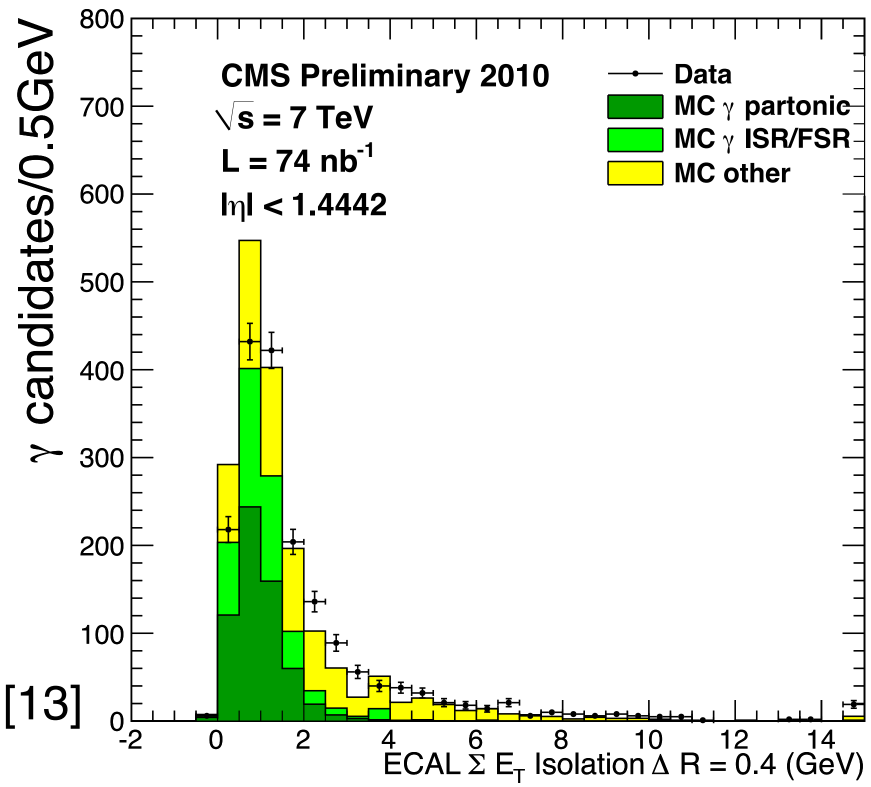
Highest energy crystal

2nd highest energy crystal

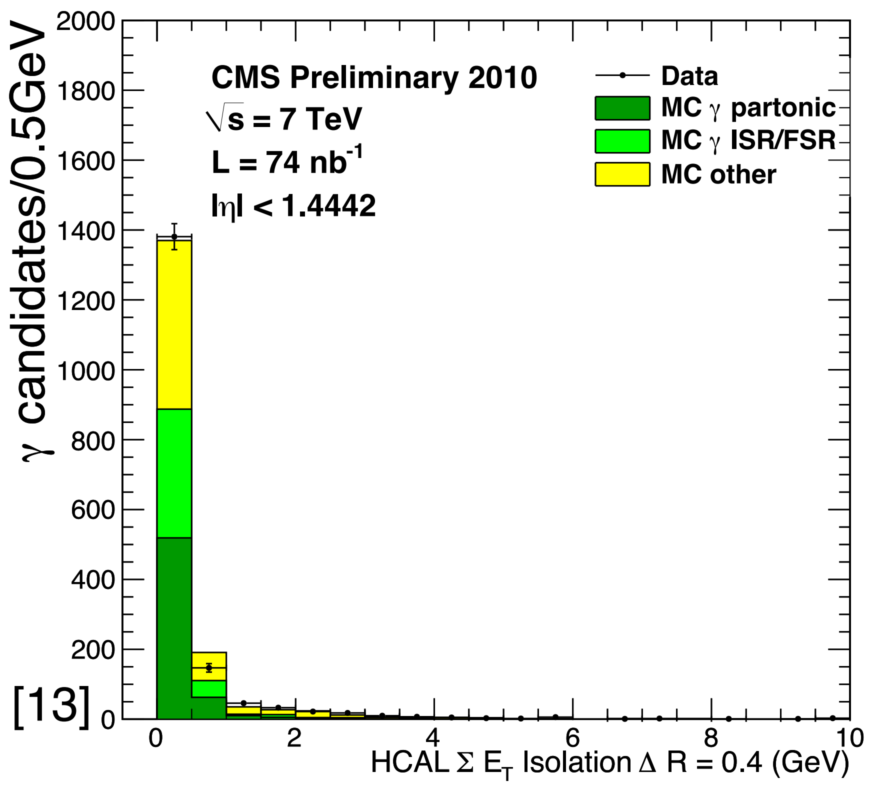
$$\frac{E_{\color{red}\blacksquare} + E_{\color{blue}\blacksquare}}{E_{3\times3}} > 0.95 \Rightarrow \text{reject}$$

1. Form 3 × 3 matrix of crystals around the photon seed crystal
2. Find the 2 highest energy crystals within the matrix
3. If the sum of the energies of the 2 highest energy crystals divided by the sum of the energies of all 9 crystals within the matrix exceeds 0.95, reject the photon as ECAL noise

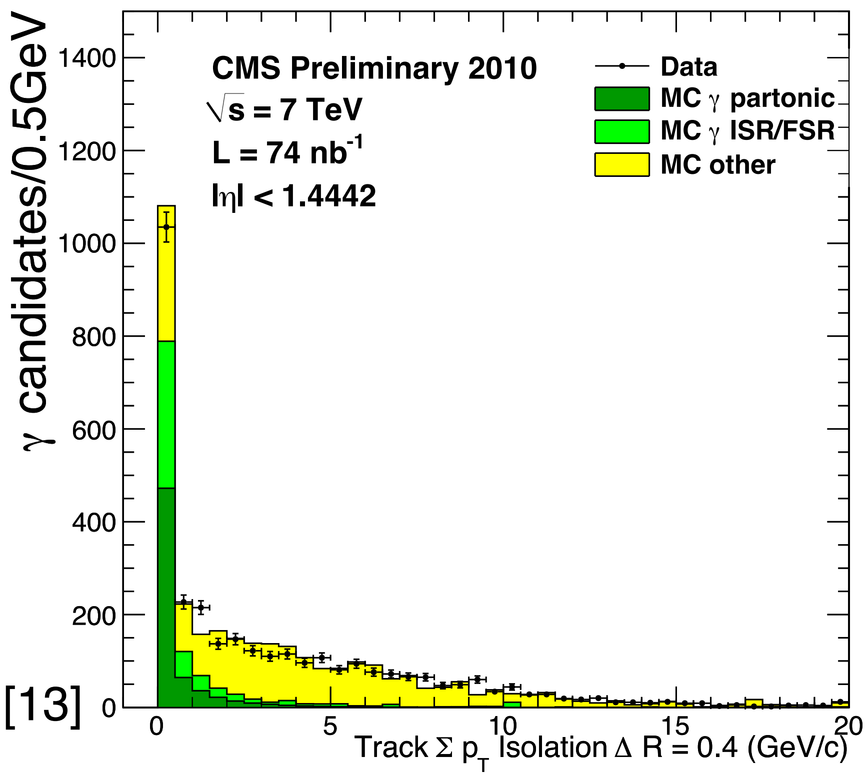
Photon ID variables



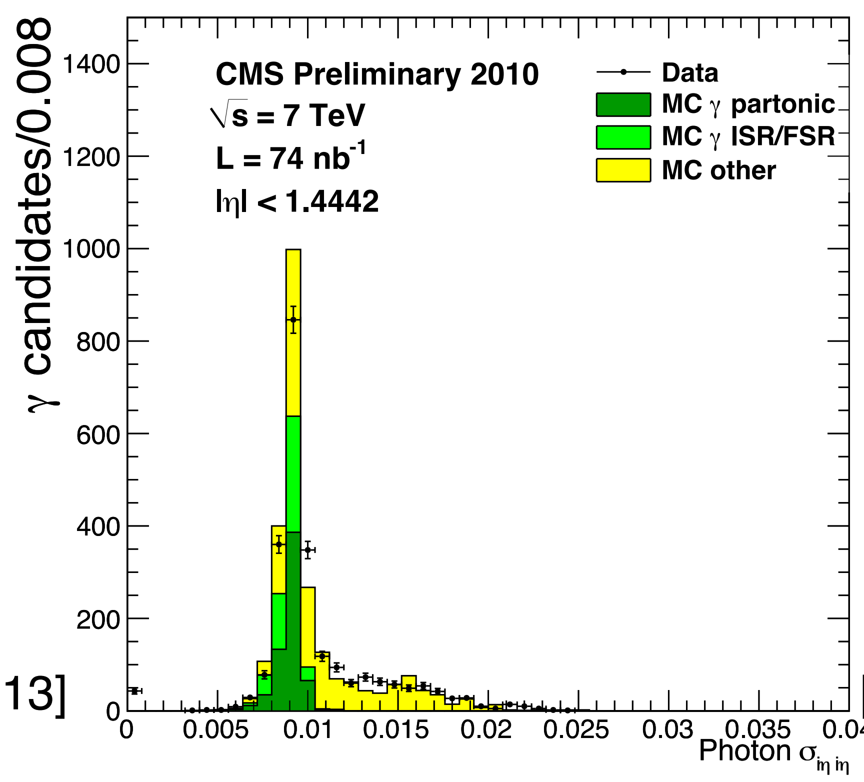
[13]



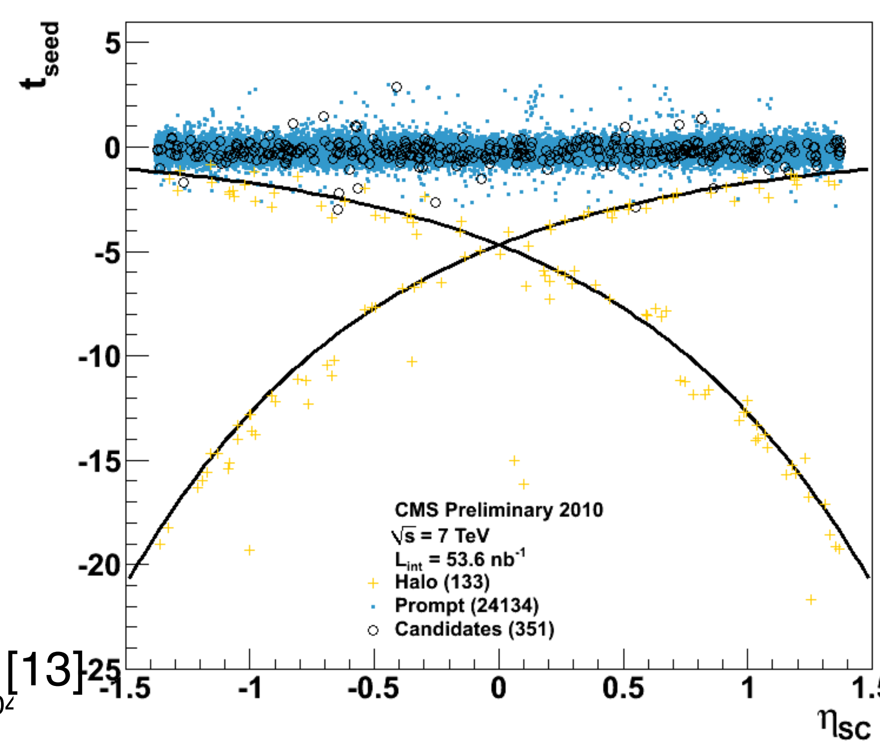
[13]



[13]



[13]



[13]

Photon/lepton ID efficiency

- Photon and lepton ID efficiencies taken from MC and corrected by (data efficiency)/(MC efficiency)
  - $Z \rightarrow \mu\mu$ events for muons
  - $Z \rightarrow ee$ events for electrons and photons
    - Photon ID cuts designed to behave similarly for electrons and photons
- Signal MC acceptance × efficiency multiplied by 1 factor of $\varepsilon_{data}/\varepsilon_{MC}$ per photon or lepton
- Pixel match veto efficiency **estimated from MC**: (96.4 ± 0.5)% (stat. ⊕ syst. due to tracker material budget variation)

Particle	$\varepsilon_{data}/\varepsilon_{MC}$
Photon	0.945 ± 0.068
Electron	0.928 ± 0.015
Muon	0.990 ± 0.001

Errors on photon efficiency scale factor:

Stat. ⊕
Syst.(Z signal and background shape variation) ⊕
Syst.(signal fit over/underestimation) ⊕
Syst.(pileup effects) ⊕
Syst.(MC electron/photon difference)

HCAL noise cleaning

1. $f_{HPD} \leq 0.98$, where f_{HPD} is the fraction of the jet's energy contributed by the highest energy hybrid photodetector
2. n90Hits > 1, where n90Hits is the minimum number of HCAL channels containing 90% of the jet's energy
3. EMF ≥ 0.01, where EMF is the electromagnetic fraction of the jet's energy

See [14]

Particle flow (PF) algorithm (1)

- Main idea: reconstruct each individual stable particle traversing the detector using an optimal combination of tracking and calorimetric information, with the aim of achieving the best possible energy resolution

1. Reconstruct the fundamental detector objects via iterative procedures
    - Tracks in the inner silicon layers
        - High efficiency and low fake rate for charged hadrons in jets
        - Relaxed primary vertex constraint allows photon conversions, particles originating from nuclear interactions in the silicon, and long-lived particles to be reconstructed
    - Calorimeter clusters
    - Muon tracks in the outer muon layers
2. Create a “block” of linked fundamental objects
    - Link silicon tracks to calorimeter clusters via $\Delta R_{\text{track-cluster}}$ (account for electron bremsstrahlung)
    - Link clusters in one calorimeter layer to clusters in a separate layer via $\Delta R_{\text{cluster-cluster}}$
    - Link silicon tracks to muon tracks via global track X^2

Particle flow (PF) algorithm (2)

3. ID the particles in the block
    - If global (silicon + muon layers) muon p_T is compatible with silicon track p_T, ID as a muon and remove corresponding tracks from block
    - ID electron tracks via special algorithm and removed all corresponding tracks and cluster from block
    - Remove fake tracks from the block
    - Remove excess track-cluster links via $\Delta R_{\text{track-cluster}}$ minimization (but allow multiple tracks to be associated to one cluster)
    - If the cluster energy is significantly larger then the energy of the linked track, ID as a PF photon or PF neutral hadron and remove corresponding clusters from the block
    - If the cluster is not linked to a track, ID as a PF photon or PF neutral hadron and remove corresponding clusters from the block
    - Remaining track-cluster links are PF charged hadrons

- Better performance in terms of jet energy resolution and jet energy correction uncertainties than typical calorimeter-only jet algorithms
- See [15] for details and performance in LHC data

Electron selection

Cut	Value		Notes
	EB	EE	EB = ECAL barrel, EE = ECAL endcap
p_T	**>20 GeV**	**>20 GeV**	
$\lvert\eta\rvert$	**<1.444**	**1.566-2.1**	1.444-1.566 is the crack between EB and EE
ECAL isolation	$<0.07E_T$	$<0.05E_T$	Same cones as on slide 27
HCAL isolation	$<0.01E_T$	$<0.025E_T$	Same cones as on slide 27
Track isolation	$<0.09E_T$	$<0.04E_T$	Same cones as on slide 27
Missing track hits	≤0	≤0	Conversion rejection cut—(expected - actual) number of hits on track
$\Delta(\cot\theta)$	<0.02	<0.02	Conversion rejection cut—θ is the polar angle between the 2 conversion clusters
Dist	<0.02	<0.02	Conversion rejection cut—distance between the 2 conversion tracks when they are parallel
$\sigma_{\eta\eta}$	<0.01	<0.03	
$\Delta\phi_{in}$	<0.06	<0.03	Between the track momentum at the primary vertex and the cluster position
$\Delta\eta_{in}$	<0.004	<0.007	Between the track momentum at the primary vertex and the cluster position
H/E	<0.04	<0.025	

Muon selection

Cut	Value	Notes
p_T	**>20 GeV**	
$\|\eta\|$	**<2.1**	Geometrical acceptance of the muon high level trigger
Combined isolation	<0.15	Combined isolation = (ECAL isolation + HCAL isolation + track isolation)/(muon p_T), cone size R = 0.3, muon track p_T and calorimeter energy subtracted
Reconstruction algorithm	Global and tracker	Tracker muon = reconstructed from tracker hits only; global muon = reconstructed from tracker and muon station hits
Muon chamber hits	≥1	
Tracker muon match	≥2 muon chambers	
Tracker hits	>10	
Pixel hits	≥1	
χ^2/ndof	<10	Global muon track fit
$\|d_{xy}\|$	<2 mm	Transverse impact parameter
High level trigger match	Yes	

Backgrounds

- Double photon
  - Dominant: **QCD with fake ME_T**
    - Multijet: at least 2 jets misidentified as photons
    - γ + jet: 1 jet misidentified as a photon
    - QCD diphoton
  - Subdominant: **electroweak processes with real ME_T**
    - W(→eν)γ: electron misidentified as a photon
    - W(→eν)+jet: electron and jet misidentified as photons
  - Negligible: irreducible backgrounds
    - Wγγ (total cross section ~7 fb at 14 TeV LHC) [6]
    - Zγγ
- Photon + lepton
  - Dominant: **W(→eν)γ, W(→μν)γ**
  - Subdominant: **jets faking photons in events with real ME_T**
    - W(→eν)+jet, W(→μν)+jet
  - Subdominant: **electrons faking photons**
    - Z→ee
    - ttbar with at least 1 W decaying to an electron
  - Subdominant: **QCD with fake ME_T**
  - Negligible: ttbar+γ
- Single photon
  - Dominant: **QCD with fake ME_T**
    - γ+jet
    - QCD multijet with at least 1 jet misidentified as a photon
  - Subdominant: **electroweak processes with real ME_T**
    - W→eν, Z→ee, or ttbar semileptonic with 1 electron misidentified as a photon
    - Initial state radiation (ISR) or final state radiation (FSR) of photons in events with no electron

Fake lepton and EM object selection

Fake electron		
Cut	Value	
	EB	EE
p_T	>20 GeV	>20 GeV
$\lvert\eta\rvert$	<1.444	1.566-2.1
ECAL isolation	$<0.07E_T$	$<0.05E_T$
HCAL isolation	$<0.01E_T$	$<0.025E_T$
Track isolation	$<0.09E_T$	$<0.04E_T$
Missing track hits	≤0	≤0
$\Delta(\cot\theta)$	<0.02	<0.02
Dist	<0.02	<0.02
$\Delta\phi_{in}$	<0.06	<0.03
$\Delta\eta_{in}$	<0.004	<0.007

EM object	
Cut	Value
p_T	>30 GeV
$\lvert\eta\rvert$	<1.4
ECAL isolation	$<(0.006E_T + 4.2\ \mathrm{GeV})$
HCAL isolation	$<(0.0025E_T + 2.2\ \mathrm{GeV})$
Track isolation	<10 GeV
H/E	<0.05
Noise-cleaned	Yes
Pixel match	No

Fake muon	
Cut	Value
p_T	>20 GeV
$\lvert\eta\rvert$	<2.1
Combined isolation	0.15-0.25
Reconstruction algorithm	Global and tracker
Muon chamber hits	≥1
Tracker muon match	≥2 muon chambers
Tracker hits	>10
Pixel hits	≥1
χ^2/ndof	<10
$\lvert d_{xy}\rvert$	<2 mm
High level trigger match	Yes

Fake electron: electron with only isolation requirements

Fake muon: muon with relaxed isolation requirement

EM object: photon with relaxed track isolation and no shower shape requirement

Event selection

- Using the CMS reconstructed physics objects, build 3 different event selections corresponding to the 3 GGM topologies

Topology	No. isolated photons	No. isolated leptons (e or μ)	No. jets	Trigger
Double photon	≥2 with: •Leading $E_T > 45$ GeV •Trailing $E_T > 30$ GeV •$\lvert\eta\rvert < 1.4442$	No requirement	≥1 with: •$E_T > 30$ GeV •$\lvert\eta\rvert < 2.6$	Single-leg seeded double photon trigger: •Leading/trailing $E_T > 32/26$, 36/22, or 40/28 GeV •Loose shower shape and H/E reqs. on both legs
Photon + lepton	≥1 with: •$E_T > 30$ GeV •$\lvert\eta\rvert < 1.4442$	≥1 with: •$E_T > 20$ GeV •$\lvert\eta\rvert < 2.1$	No requirement	Single-lepton trigger: •$E_T > 15$ or 17 GeV (electron) •$E_T > 9$, 11, or 15 GeV (muon)
Single photon	≥1 with: •$E_T > 75$ GeV •$\lvert\eta\rvert < 1.4442$	No requirement	≥3 with: •$E_T > 30$ GeV •$\lvert\eta\rvert < 2.6$ + $H_T^* > 400$ GeV	Single-photon + H_T trigger: •Photon $E_T > 70$ GeV •$H_T > 350$ GeV

*H_T is the scalar sum of jet p_T in the event

Single fake definition

Cut	Value
p_T	>70 GeV
$\|\eta\|$	<1.4442
ECAL isolation	<min(10 × (0.006E_T + 4.2 GeV), 0.3E_T)
HCAL isolation	<min(10 × (0.0025E_T + 2.2 GeV), 0.3E_T)
Track isolation	<min(10 × (0.001E_T + 3.5 GeV), 0.3E_T)
Pixel seed	No
R9	<0.98
Trigger	Yes

and

Cut	Value
ECAL isolation	>(0.006E_T + 4.2 GeV)
and	
HCAL isolation	>(0.0025E_T + 2.2 GeV)
or	
Track isolation	>(0.001E_T + 3.5 GeV)
or	
$\sigma_{\eta\eta}$	>0.011
or	
H/E	>0.05

$f_{e\to\gamma}$ calculation

The number of events in the di-electron sample is given by

$$N_{ee} = f^2_{e\to e} N_{Z\to ee}$$

where $f_{e\to e}$ is the efficiency to correctly identify an electron via pixel match and $N_{Z\to ee}$ is the true number of Z→ee events. The number of events in the eγ sample due to misidentification of 1 Z electron as a photon is given by

$$N^Z_{e\gamma} = 2 f_{e\to e}(1 - f_{e\to e}) N_{Z\to ee}$$

Solving for $f_{e\to e}$,

$$f_{e\to e} = \frac{1}{1+\frac{1}{2}\frac{N^Z_{e\gamma}}{N_{ee}}}$$

The number of events in the eγ sample due to correctly identifying a W electron is given by

$$N^W_{e\gamma} = f_{e\to e} N_W$$

where N_W is the number of true W→eν events. The number of $\gamma\gamma$ events from W electron misidentification is given by

$$N^{EW}_{\gamma\gamma} = (1 - f_{e\to e}) N_W$$

where we have neglected the contribution from Z electron misidentification since it is small (i.e., $f_{e\to\gamma}$ is small and the Z contribution involves $f^2_{e\to\gamma}$, since both electrons have to be misidentified). Since

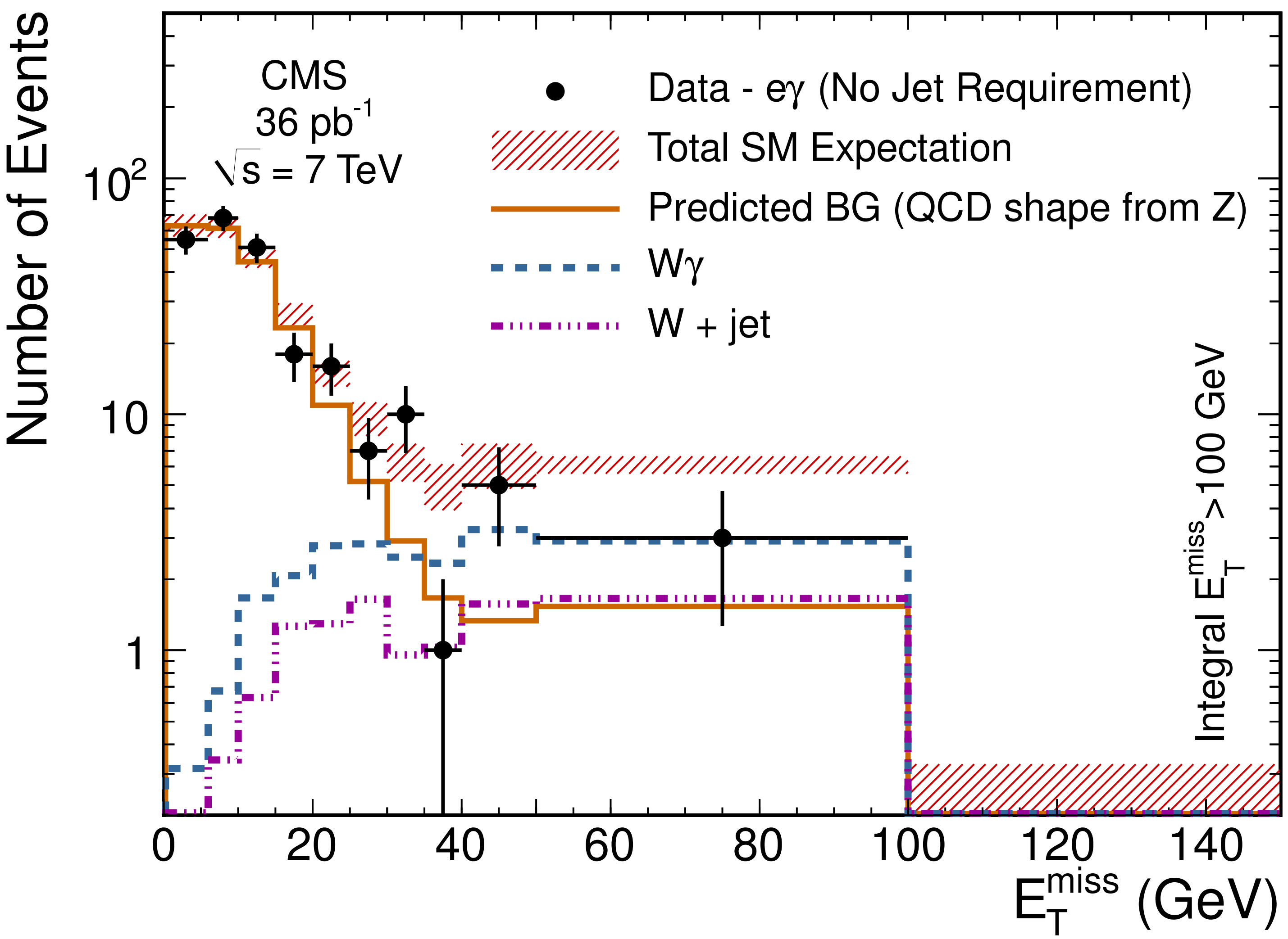
$$f_{e\to e} = 1 - f_{e\to\gamma}$$

solving for $N^{EW}_{\gamma\gamma}$

$$N^{EW}_{\gamma\gamma} = \frac{f_{e\to\gamma}}{1-f_{e\to\gamma}} N_{e\to\gamma}$$

Check of the background estimation

- Question: Can the QCD background prediction method described on slide 11 correctly predict the QCD contribution to the eγ (W-like) sample?
- Answer: Yes
  - Reweight the di-electron ME_T spectrum such that the di-electron p_T spectrum matches the eγ di-EM p_T spectrum (i.e. use the method described on slide 11 to get a prediction for the QCD component of the eγ sample)
  - Observe an excess (esp. for $ME_T > 30$ GeV) of eγ events over the predicted QCD background
  - Excess is consistent with expected yield of Wγ and W+jet Monte Carlo (MC)



Estimating the jet→γ backgrounds

- Jet→γ fake rate determination
  - Muon-, jet-, and photon-triggered datasets to determine the fake rate
  - Fake rate = (# of photons)/(# of fakeable objects)
    - Fakeable object: still EM-like, but failing some important photon ID cuts
  - Real photon component in tight photon sample extracted from fit to MC shower shape template and subtracted
  - Strong dependence on p_T, no dependence on $|\eta|$ in EB
- ME_T spectrum of **lepton + fakeable object** data control sample weighted by E_T-dependent fake rate

Fakeable object definition:

Cut	Value
p_T	>20 GeV
$\|\eta\|$	<1.4
ECAL isolation	<min(5 × (0.006E_T + 4.2 GeV), 0.2E_T)
HCAL isolation	<min(5 × (0.0025E_T + 2.2 GeV), 0.2E_T)
Track isolation	<min(5 × (0.001E_T + 3.5 GeV), 0.2E_T)

and

Cut	Value
ECAL isolation	>(0.006E_T + 4.2 GeV)
or	
HCAL isolation	>(0.0025E_T + 2.2 GeV)
or	
Track isolation	>(0.001E_T + 3.5 GeV)
or	
$\sigma_{\eta\eta}$	>0.013

Estimating backgrounds from MC

Syst.(10% from halving/doubling factorization and renormalization scale) ⊕
syst.(<2% PDF uncertainty [16]) ⊕
syst.(4% luminosity)

- **Wγ background in photon + lepton search** →
  - Modeled with **MadGraph MC**, tune D6T
  - K-factors estimated from BAUR NLO generator using CTEQ66 NLO PDF sets
  - K-factors range from ~2-3, depending on photon E_T
  - Leading order photon E_T spectrum modified by K-factors, but ME_T and M_T distributions are much more stable with respect to NLO effects
- Background to **single photon search from ttbar/W/Z→hadrons + ISR/FSR photon** is small (total <1 event in $ME_T \geq 200$ GeV vs. ~10 events from other background sources) and taken from Pythia MC simulation with 100% uncertainty

Table of backgrounds

Type	Events	stat. error	scal. error	norm. error
$\gamma\gamma$ candidates	0			
ff QCD background	2.3 ± 2.2	± 2.19	± 0.13	± 0.10
ee QCD background	0.8 ± 0.8	± 0.82	± 0.02	± 0.03
EWK background	0.3 ± 0.1	± 0.06	± 0.0	± 0.03
Total background (ff)	2.5 ± 2.2			
Total background (ee)	1.3 ± 0.8			

Double photon

Sample	Event yield		
		(stat.)	(syst.)
Data	7		
QCD (est. from data)	5.16	± 2.58	± 0.62
EWK $e \to \gamma$ (est. from data)	1.22	± 0.13	± 0.04
FSR/ISR ($W \to \mu/\tau\nu, Z \to \nu\nu$) (Sim.)	0.80	± 0.31	± 0.80
FSR/ISR ($t\bar{t} \to \mu/\tau\nu + X$) (Sim.)	0.07	± 0.05	± 0.07
Total SM background estimate	7.24	± 2.6	± 1.53

Single photon

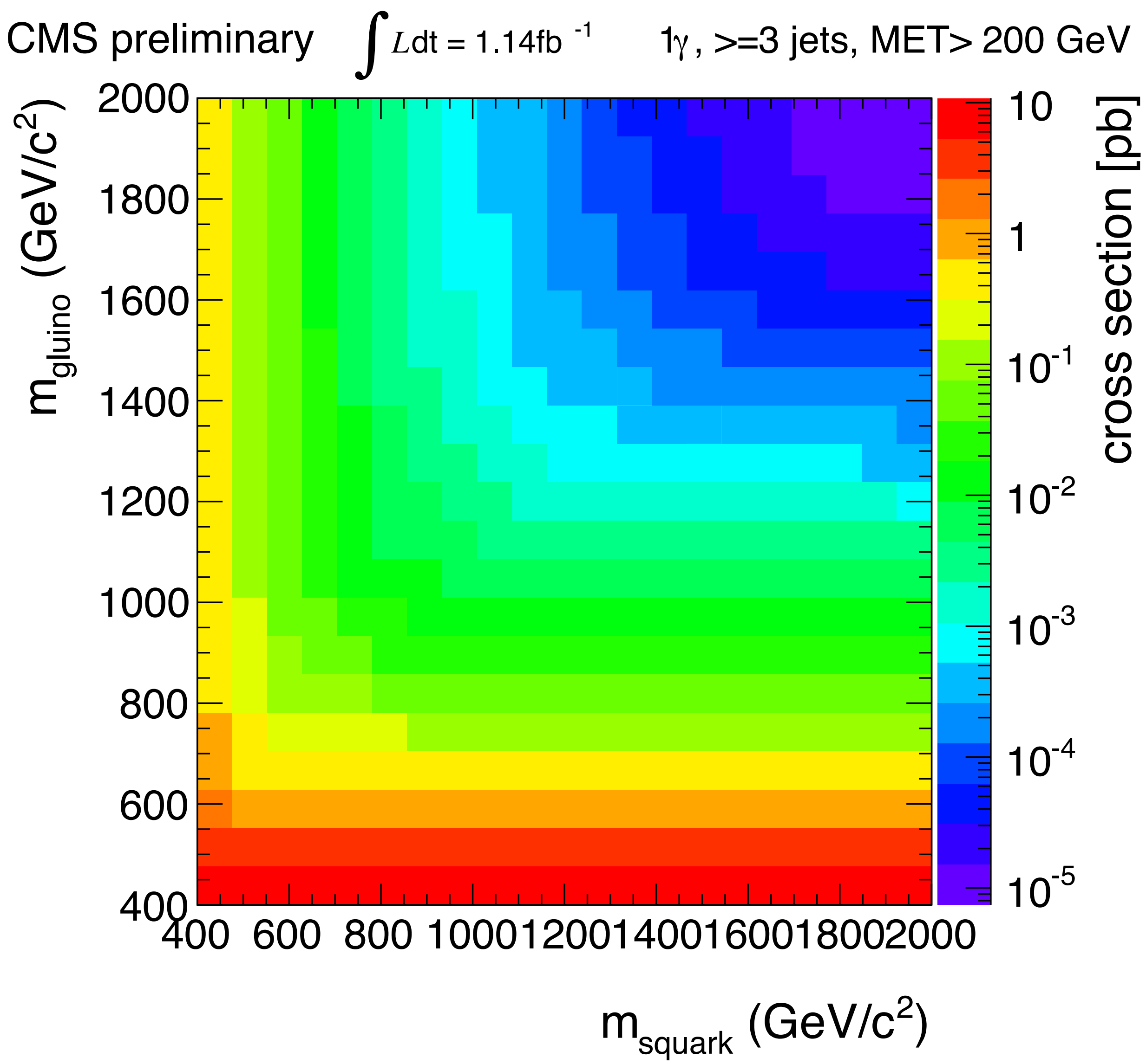
Errors: stat. $\oplus$ syst.(ME_T shape from reweighting) $\oplus$ syst.(normalization)

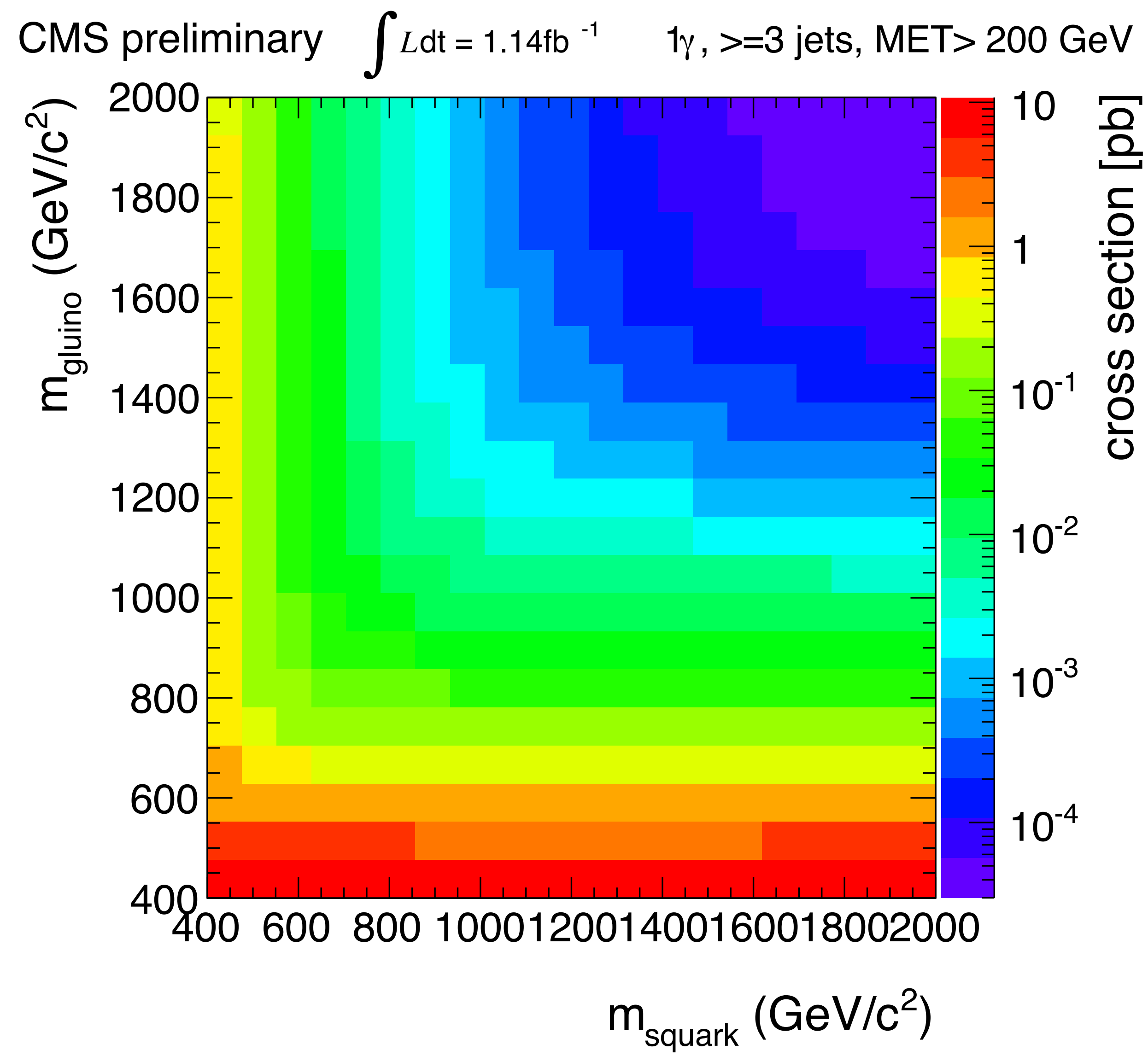
e+γ+ME_T	
Sample	$ME_T > 100$ GeV
Wγ (MC)	1.68 ± 0.42
jet→γ	0.02 ± 0.02
e→γ	0.04 ± 0.03
QCD (di-e pred.)	0.00 ± 0.00
Total background	**1.74 ± 0.43**
Data	**1**
GGM prediction	**3.38 ± 0.68**

μ+γ+ME_T	
Sample	$ME_T > 100$ GeV
Wγ (MC)	1.40 ± 0.37
jet→γ	0.10 ± 0.09
e→γ	0.09 ± 0.04
QCD (di-e pred.)	0.00 ± 0.00
Total background	**1.59 ± 0.39**
Data	**1**
GGM prediction	**4.41 ± 0.88**

Photon + lepton

NLO cross sections

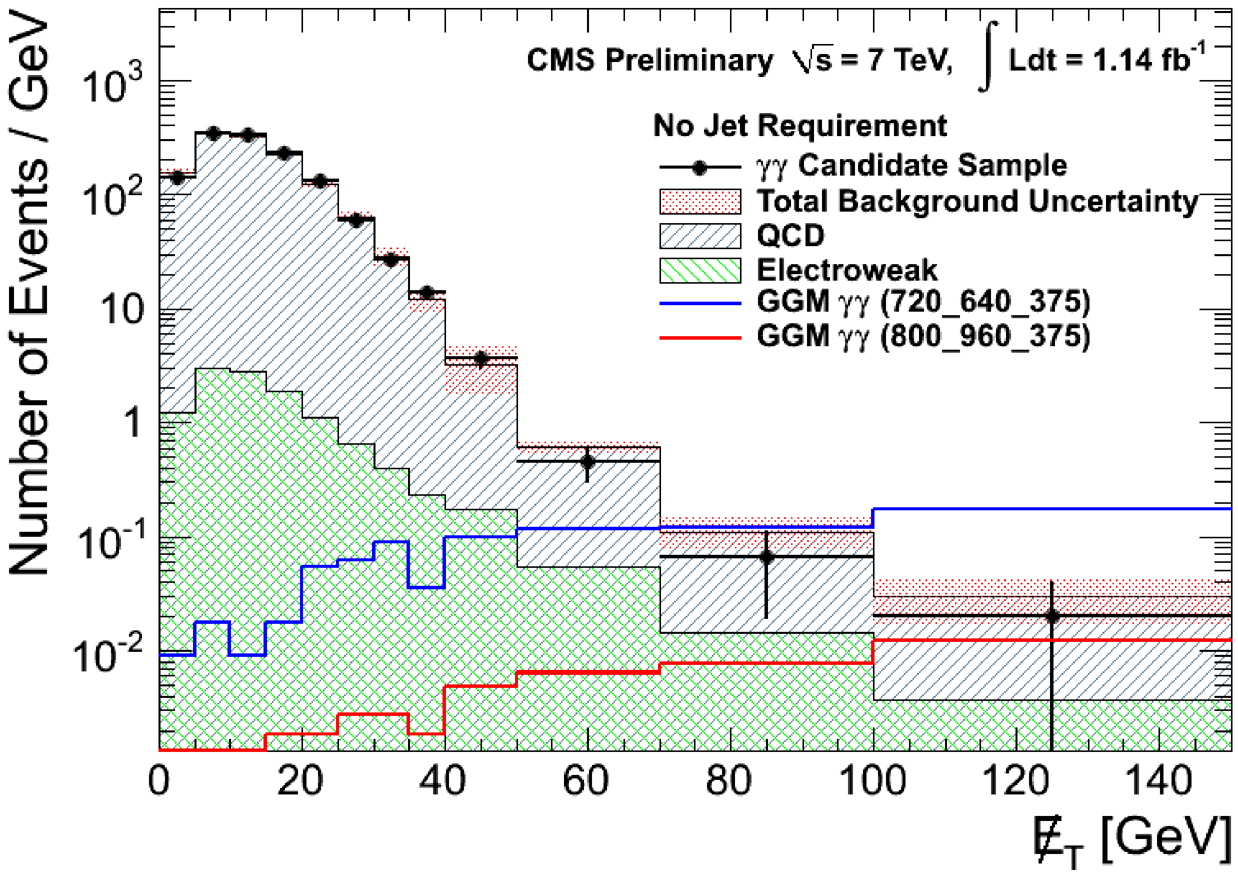




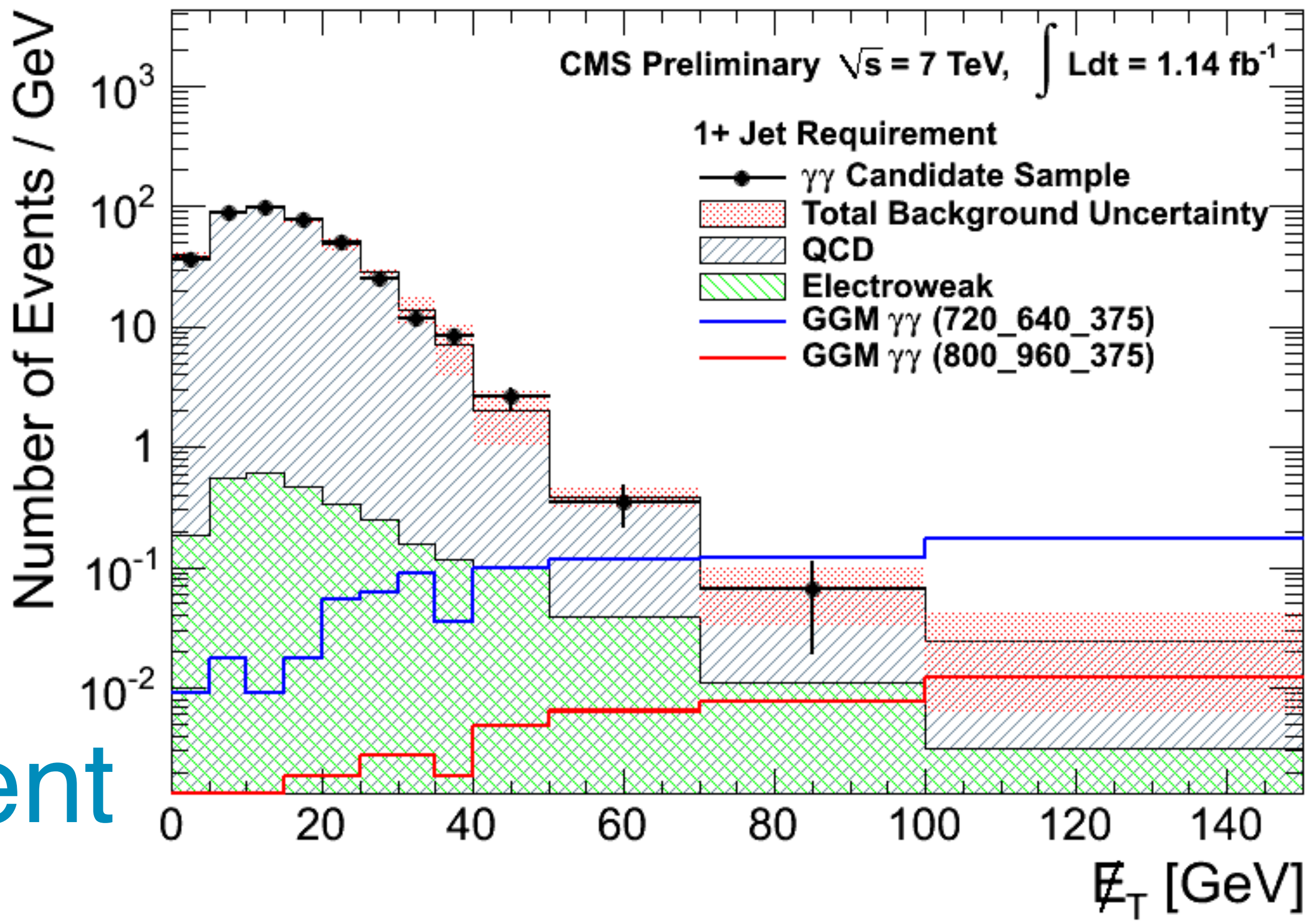
Bino NLSP

Wino NLSP

ME_T with(out) jet requirement

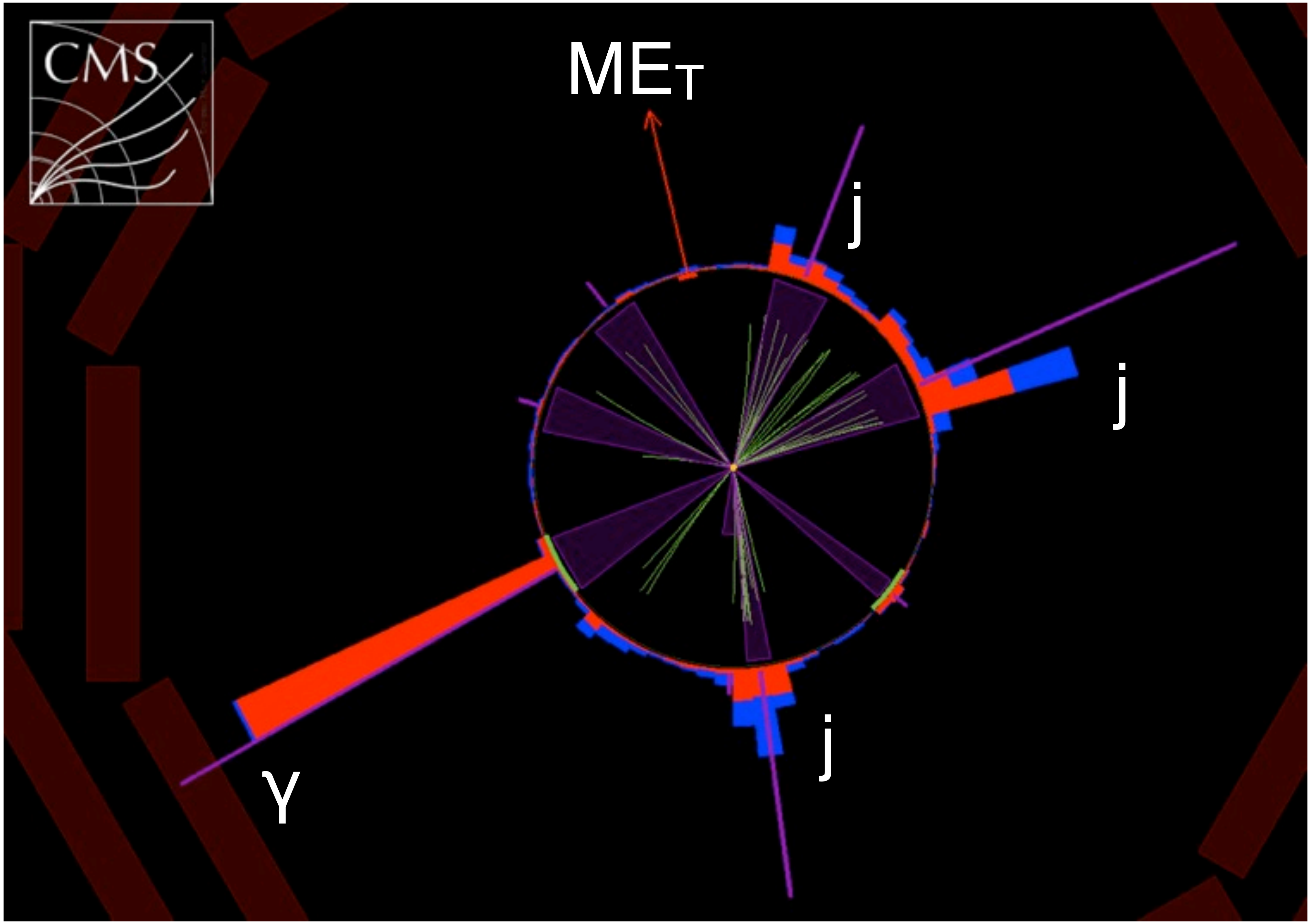


No jet requirement



1+ jet requirement

Simulated GGM single photon event display



References

1. A. García-Bellido, arXiv:hep-ex/0210001v1 (2002).
2. B.C. Allanach et al., Eur. Phys. J. **C25** (2002) 113.
3. V. Abazov et al., Phys. Rev. Lett. **105** (2010) 221802.
4. B. Brau, arXiv:1007.2244v2 [hep-ex] (2011).
5. CERN/LHCC 97-33 (1997).
6. G. Bozzi, F. Campanario, M. Rauch, D. Zeppenfeld, arXiv:1103.4613v1 [hep-ph] (2011).
7. http://lhcnewphysics.org/p.000.00.r000
8. M. Botje et al., arXiv:1101.0538v1 [hep-ph] (2011).
9. A. Read, J. Phys. G **28** (2002) 2693.
10. K. Nakamura et al., J. Phys. G **37** (2010) 075021.
11. C. Quigg, arXiv:0908.3660v2 [hep-ph] (2009).
12. CMS Collaboration, CERN-PH-EP/2010-053 (2010).
13. CMS-PAS-EGM-10-005 (2010).
14. CERN-CMS-DP-2010-014 (2010).
15. CMS Collaboration, CERN-PH-EP/2011-102 (2011).
16. D. Bourilkov, R.C. Group, M. R. Whalley, arXiv:hep-ph/0605240v2 (2006); http://www.hep.ucl.ac.uk/pdf4lhc/PDF4LHCrecom.pdf (2010).